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ESTIMATING SOIL SALINITY USING REMOTE SENSING DATA

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INTRODUCTION

Soil salinity is a severe environmental hazard (Hillel 2000) that impacts the growth of many crops. Human-induced salinization is the result of salt stored in the soil profile being mobilized by extra water provided by human activities such as irrigation (Szabolcs 1989). Salinization problems continue to spread around the world at a rate of up to 2 million hectares a year, offsetting a good portion of the increased productivity achieved by expanding irrigation (Postel 1999). Since the irrigated acreage in Colorado is fairly stable, any increase in soil salinity will have a direct impact on the agricultural production of the state.

Remotely sensed data has great potential for monitoring dynamic processes, including salinization. Remote sensing of surface features using aerial photography, videography, infrared thermometry, and multispectral scanners has been used intensively to identify and map salt-affected areas (Robbins and Wiegand 1990). Metternicht and Zinck (1997) provided an approach for mapping salt- and sodium-affected surfaces by combining digital image classification with field observation of soil degradation features and laboratory determinations in the semiarid valleys of Cochabamba, Bolivia. Multispectral data acquired from platforms such as Landsat, SPOT, and the Indian Remote Sensing (IRS) series of satellites have been found to be useful in detecting, mapping and monitoring salt-affected soils (Dwivedi and Rao 1992).

Band ratios of visible to near-infrared and between infrared bands have proven to be better for identifying salts in soils and salt-stressed crops than individual bands (Craig et al., 1998 and Hick and Russell, 1990). Wiegand et al. (1994) carried out a procedure to assess the extent and severity of soil salinity in fields in terms of economic impact on crop production and effectiveness of reclamation efforts. Their results illustrate practical ways to combine image analysis capability, spectral observations, and ground truth to map and quantify the severity of soil salinity and its effects on crops.

Ghabour and Daels (1993) concluded that detection of soil degradation by conventional means of soil surveying requires a great deal of time, but remote sensing data and techniques offer the possibility for mapping and monitoring these processes more efficiently and economically. However, to assess the accuracy of the ability of satellite images to map and monitor salinity, it is necessary to compare them with field measurements of salinity. Our research uses remote sensing techniques for the purpose of determining the spatial and temporal (if multiple images are used from different dates) extent and magnitude of salt-affected areas. We have focused our initial studies in an area around La Junta, in the Arkansas Valley of Colorado. We have used extensive field data to validate the accuracy of the remote sensing techniques.

METHODOLOGY

The approach presented in this paper involves integrating remote sensing data, Geographic Information System (GIS), and spatial analysis to predict soil salinity. First, soil salinity data was collected in the field. The locations of the field samples were recorded on a Global Positioning System (GPS) unit, and a GIS map was generated. The collected soil salinity data was tied to the corresponding points on a georeferenced Ikonos satellite image. The soil salinity data are tested against the blue, green, red, and infrared bands of the satellite image as well as the normalized difference vegetation index (NDVI) and the infrared band divided by the red band (IR/R). Stepwise regression is used to determine the combination of bands that best relate to soil salinity. Ordinary least squares (OLS), spatial autoregressive (SAR), and spatial lag (SLAG) models are used as regression models to correlate the variables. The weighted average of the resultant matrix from the soil salinity data and the corresponding value from the satellite imagery is determined.

We are also testing a second approach in which we assume that the crop condition is the main indicator of the presence and severity of saline soils. Elevated levels of soil salinity will affect the growth of most crops as well as their appearance. This can be detected remotely using satellite images. By enhancing the image, we can separate the crop condition into several classes. Using spatially referenced ground data collected at the study area, we can relate each class in the satellite image to a level of soil salinity. We can use these classes to create a signature file to classify other areas planted with the same crop.

As part of this project we have collected soil samples from over 100 locations, with each sample being comprised of four depths (1, 2, 3, and 4 feet). These samples were analyzed using the HACH SIW Salinity Appraisal, and a composite EC_e (the average of four sub samples at each 1 foot depth) was calculated for each sample. The calculated EC_e values were compared to the EM-38 readings that were taken at each sample point. After multiple iterations it was decided that a linear regression between the EM-38 vertical reading and the EC_e provided the best match (Figure 1). From these data we developed the following regression model that converts EM-38 vertical readings into dS/m values:

$F = (SStemp-25)/10$
where: SStemp = temperature of soil sample measured in deg C
$A = 1-0.203462\, F + 0.038223\, (F^2) - 0.005554\, (F^3)$
$SSTc = A * SStemp$ (where: SSTc = temperature correction factor)
$EM_{Vc} = EM_V * SSTc$ (where: EM_{Vc} = Temperature corrected EM-38 vertical reading)
$EC_e = 0.0877 * EM_{Vc} + 1.8303$

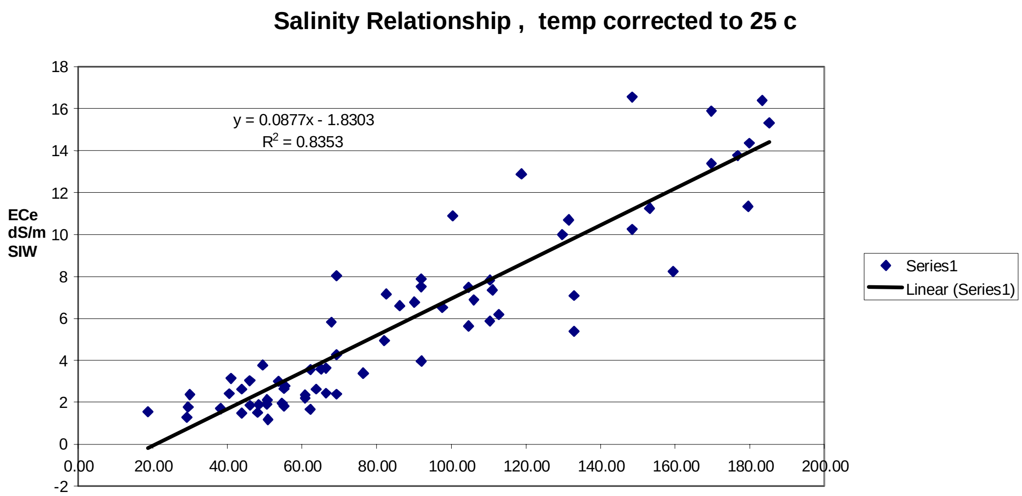

Figure 1. Regression equation relating EM_v and EC_e.

If equations with better correlations are developed to relate EM-38 readings to $EC_{e,}$ the work presented here can be updated to reflect these new equations. However the methodology and approach will remain the same.

Analysis and Results

The criteria for selecting the best model are that it should have the smallest Akaike Information Corrected Criteria (AICC), a small standard error, a p-value of each selected variable less than 0.05, and a p-value of Moran's I of residuals larger than 0.05. For the combination of variables shown in Table 1, the OLS model using a combination of the blue band, infrared band, NDVI, and IR/R created the most accurate map of soil salinity for the given combination of variables. The SAR model was rejected because the p-value of the blue band was 0.3739. The SLAG model was also rejected because the p-values for both blue and infrared bands were larger than 0.05. For the OLS model, the p-value of Lagrange was 0 and the p-value of Moran's I was greater than 0.05. The equation to predict soil salinity based on the results of the OLS model is:

OLS predicted soil salinity = 8.5537 + 0.0099 * blue band – 0.87 * infrared band – 5.1164 * NDVI + 0.8918 * IR/R.

Table 1. The output variable results of OLS, SAR, and SLAG models using blue, infrared, NDVI, and IR/R.

Variable		OLS	SAR	SLAG
	R^2	0.524	0.2484	0.2401
	Residual Standard error	1.5598	1.3299	1.3544
Intercept	Coefficient	8.5537	7.6347	3.3836
	p-value	0	0.0106	0.0276
	Standard Error	1.7585	2.9651	1.527
Blue band	Coefficient	0.0099	0.0055	-0.0007
	p-value	0.0372	0.3739	0.868
	Standard Error	0.0047	0.0062	0.0041
Infrared Band	Coefficient	-0.0087	-0.006	-0.0008
	p-value	0.0001	0.0187	0.6815
	Standard Error	0.0022	0.0025	0.0019
NDVI	Coefficient	-5.1164	-6.8724	-8.9754
	p-value	0.0174	0.0042	0
	Standard Error	2.1378	2.3808	1.8563
IR/R	Coefficient	0.8918	1.004	0.8289
	p-value	0.0113	0.0043	0.0068
	Standard Error	0.3496	0.3486	0.3035
Lambda	Coefficient		0.9364	
	p-value		0	
	Standard Error		0.0344	
AICC		963.03	894.9011	900.4215
Moran’s I (residuals)		0.1741		
p-value of Moran’s I		0.3814		
p-value (Lagrange)		0		
Likelihood *p*-value			0	0

Figure 2 illustrates different ways of analyzing residuals, including a residuals histogram and graphs of the residuals versus the neighborhood number, predicted values, and the weight of residuals. The residuals histogram has a normal distribution which means that the residuals are spatially independent. The analysis of the residuals versus the neighborhood number, predicted values and the weight of residuals show that there is no clear trend for any residual which confirms that the residuals are spatially independent.

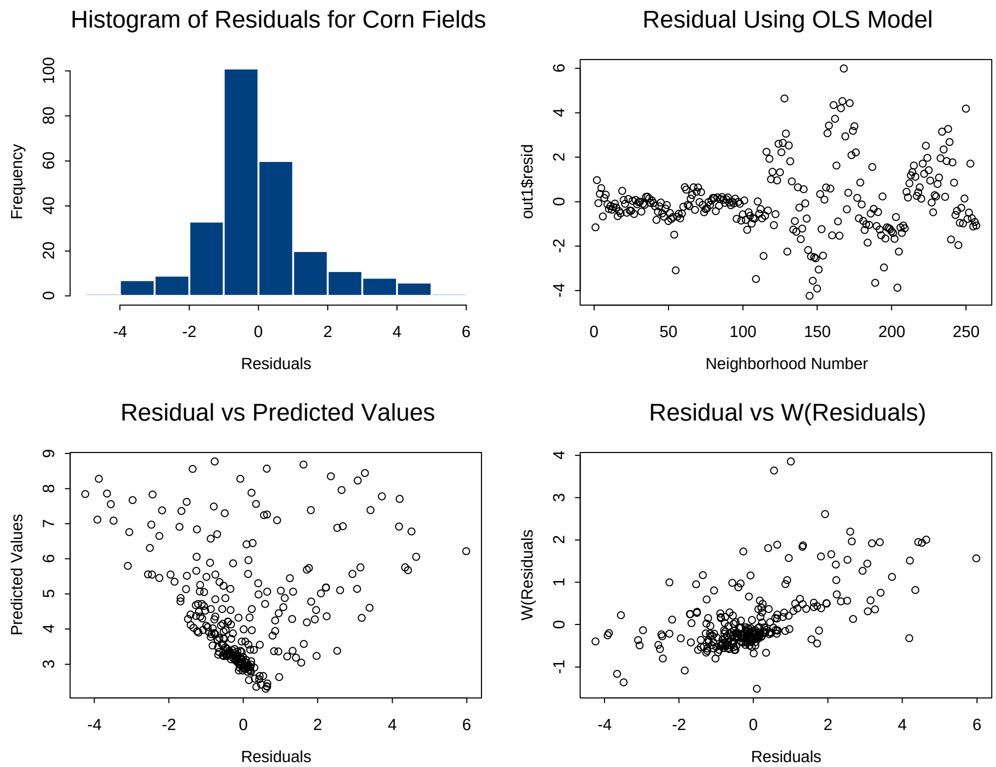

Figure 2. Histogram of residuals and residuals versus neighborhood number, predicted values of soil salinity, and weight of residuals for the OLS when using the blue, infrared, NDVI, and IR/R.

A second set of band combinations was evaluated and the results are shown in Table 2. For this set of band combinations the results show that the SAR model was the best model. The SLAG model was rejected because the p-value of the infrared band was larger than 0.05. The OLS model had a larger AICC than the SAR model, causing the OLS model to be rejected. The equation to predict soil salinity based on the results of the SAR model is:

SAR Predicted soil salinity = 9.6914 – 0.0047 * infrared band – 8.3907 * NDVI + 0.8743 * IR/R.

Table 2. The output variable results of OLS, SAR, and SLAG models using infrared, NDVI, and IR/R.

Variable		OLS	SAR	SLAG
	R^2	0.5157	0.2469	0.2413
	Residual Standard Error	1.5702	1.3295	1.3521
Intercept	Coefficient	11.7136	9.6914	3.1976
	p-value	0	0	0.0001
	Standard Error	0.9092	1.8635	0.7829
Infrared Band	Coefficient	-0.0052	-0.0047	-0.001
	p-value	0.0006	0.024	0.4136
	Standard Error	0.0015	0.0021	0.0013
NDVI	Coefficient	-7.6721	-8.3907	-8.7948
	p-value	0	0	0
	Standard Error	1.767	1.6657	1.5215
IR/R	Coefficient	0.4692	0.8743	0.8566
	p-value	0.1037	0.0063	0
	Standard Error	0.2873	0.3172	1.5215
Lambda	Coefficient		0.9354	
	p-value		0	
	Standard Error		0.0348	
AICC		965.3819	893.6044	898.3511
Moran's I (residuals)		0.1837		
p-value of Moran's I		0.3713		
p-value (Lagrange)		0		
Likelihood *p*-value			0	0

The histogram of residuals shown in Figure 3 has a distribution which is very close to normal, meaning that there is no correlation among the residuals and the residuals are spatially independent. The other three parts of the figure also confirm that there is no correlation among the residuals and that they are spatially independent.

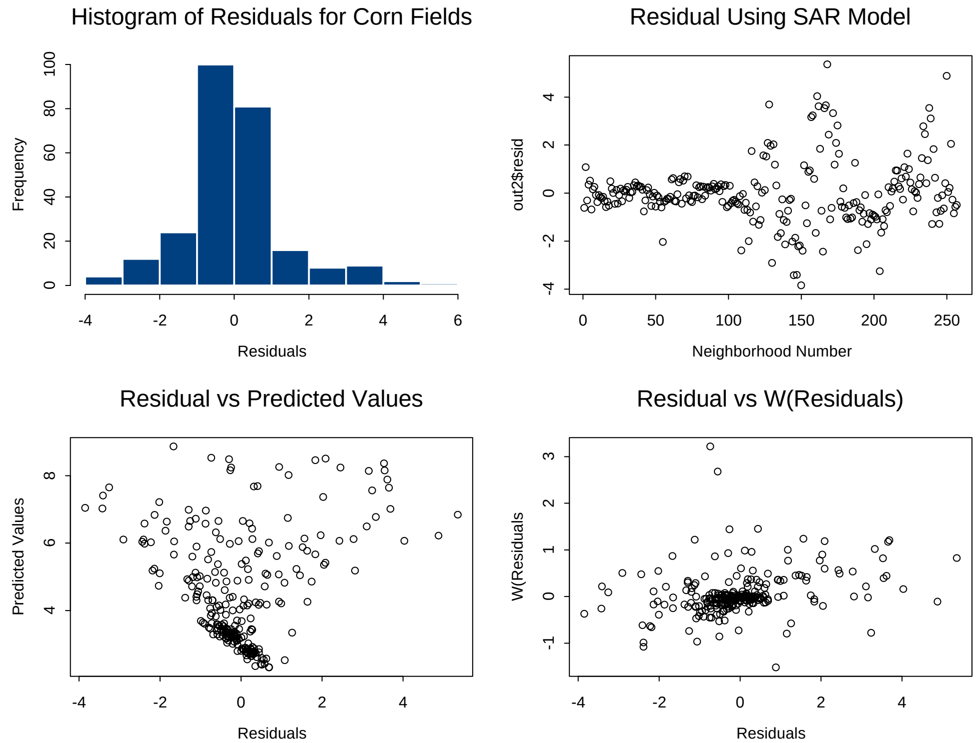

Figure 3. Histogram of residuals and residuals versus neighborhood number, predicted values of soil salinity, and weight of residuals when using the SAR model for infrared, NDVI, and IR/R.

As mentioned earlier, a second approach to detecting soil salinity that we have been testing is to assume that the crop condition is the main indicator of the presence and severity of saline soils. For this approach we selected a field with significant spatial variability in soil salinity (varying from less than 1 dS/m, which causes no crop loss, to over 7.5 dS/m, which inflicts severe corn crop loss) to be our calibration field. A field which fits this criterion is shown in Figure 4. The salinity of the field was determined using georeferenced EM-38 readings. This calibration field allowed us to separate as many salinity classes as possible. Nine different salinity levels were separated from the calibration field. To separate these levels, we spatially linked the satellite image with the soil salinity map derived from field readings. Using a combination of 3 bands (blue, green and near IR) in the satellite image, we selected several pixels that specifically corresponded to a soil salinity level. Reflectance values ranged from 200- 800, with high salinity points clustered around the 700 pixel value, moderate salinity points around the 400-500 pixel value and low salinity points around the 200 pixel value. The classified image was re-coded based on the soil salinity map obtained previously using the EM-38. This re-coding was accomplished by spatially matching each class with the soil salinity values in the same area. This process yielded three classes that represent the severity of soil salinity. The classes were low (0-3.8 dS/m), moderate (3.8-5.8 dS/m) and high (>5.8 dS/m).

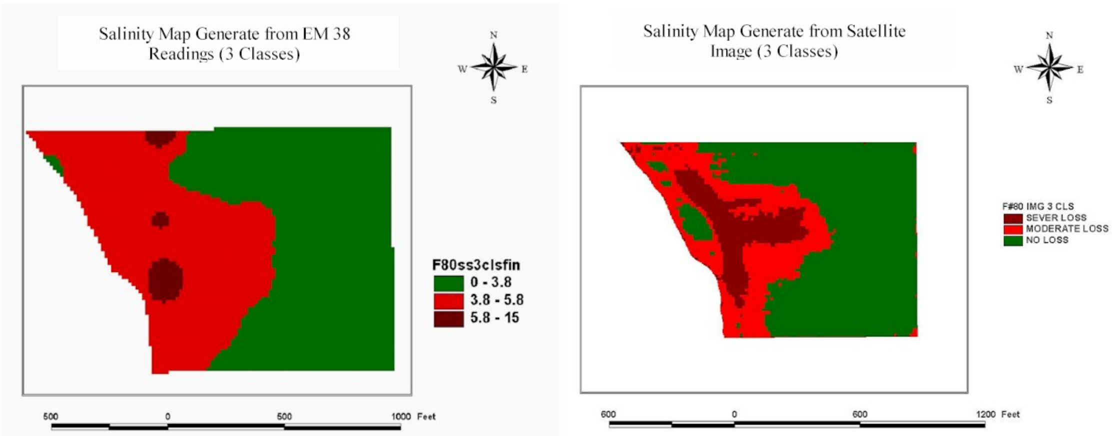

Figure 4. Soil salinity map generated from field data vs. map generated from satellite image.

To examine the accuracy of the satellite generated map, a comparison was done between the ground data map and the re-coded satellite image. The histograms in Figure 5 show this comparison. Fifty five percent of the field-data generated map had soil salinity levels of less than 3.8 dS/m. In the satellite map, 62% of the field registered no loss, indicating salinity levels of less than 3.8 dS/m. Areas where soil salinity levels ranged from 3.8 to 5.8 are considered moderate loss areas and covered 42% of the field in the map generated by the field data. In the satellite image, moderate loss areas comprised 25% of the field area. The highest crop loss falls within areas that have soil salinity of over 5.8 dS/m. These areas encompassed 3% of the field in the field-data generated map. In the satellite image 13% of the field is shown to have severe loss.

To validate this approach, the soil salinity was mapped using an EM-38 in another corn field that falls within the calibrated image. In this validation field, 64 EM-38 soil salinity measurements were taken. A map was generated that shows the severity of the soil salinity in the validation field expressed in terms of low (0-3.8 dS/m), moderate (3.8-5.8 dS/m) and high (>5.8 dS/m) levels.

Table 3 compares the soil salinity map generated from the satellite image with the soil salinity map generated from the EM-38 measurements for the validation field. The comparison shows there was less error when mapping the low salinity areas, which was expected because of the uniformity of the crop in the low salinity areas. No errors were generated when mapping the high salinity zones.

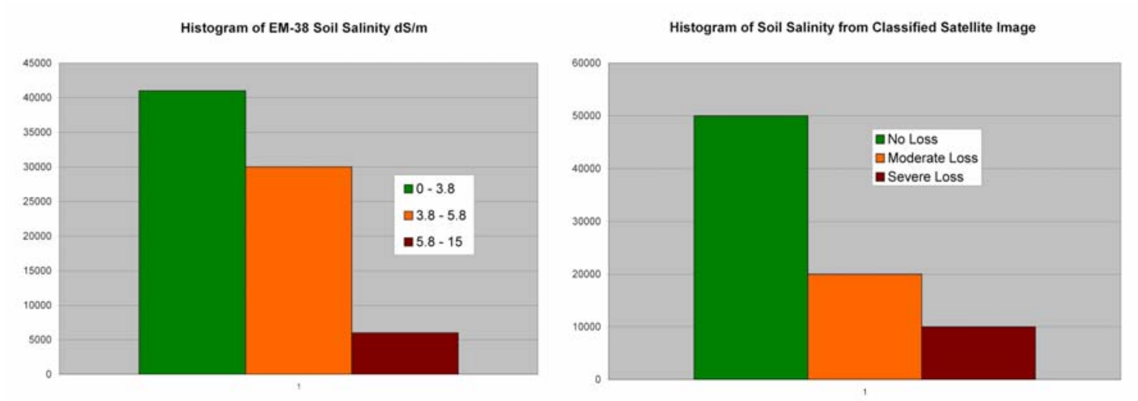

Figure 3. Histogram developed from the maps generated from the EM-38 and the satellite image.

Table 3. Percentage comparisons of salinity levels shown in the two maps.

Class	Ground Data (EM-38)	From Satellite Image
Low salinity	72.53 %	66.17 %
Moderate	22.05 %	21.53 %
High salinity	5.42 %	12.29 %

The over estimation of the high salinity area was because of the existence of a road on the west edge of the field which was classified as a high salinity area because it has no vegetation. Such errors could be eliminated by masking roads and canals as well as bare soil areas (such as barns or feedlots) in the classified image.

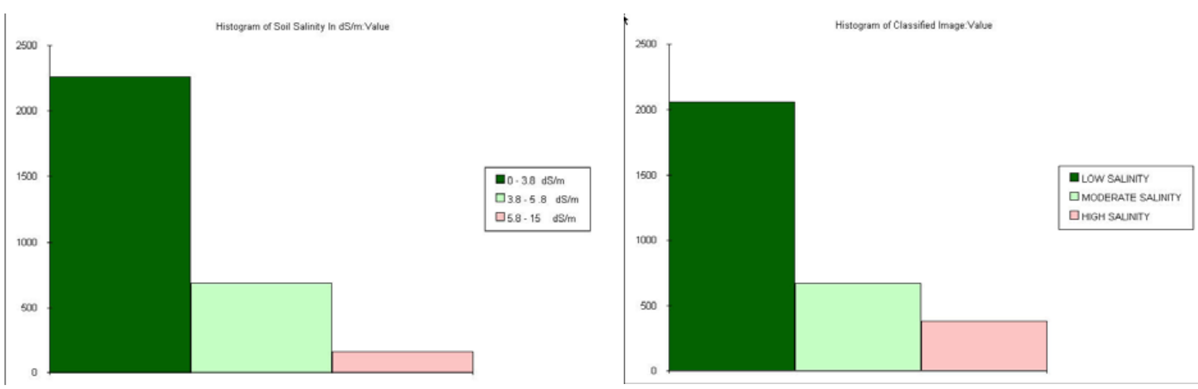

Figure 4. Histogram comparison of the salinity map generated from field data vs. the satellite image map.

SUMMARY AND CONCLUSION

The results presented in this paper show the feasibility of using remote sensing data to estimate soil salinity for corn fields. Compared to the labor, time, and money invested in field work devoted to collecting soil salinity data, the availability and ease of acquiring satellite imagery is very attractive. The results of our two approaches were:

1) Stepwise regression yields the best combinations of bands to use 90% of the time. The SAR model using the infrared, NDVI, and IR/R combination was evaluated to be the best of all the tested models as it satisfied all the selection criteria and has the smallest AICC value.
2) The approach using crop condition as the main indicator of saline soils has worked very well in our study area. The histogram comparison in Figure 4 shows that the calibrated satellite image matched the data collected with the EM-38 with an overall error of less than 15%.

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ADVANTAGES AND LIMITATIONS OF ET-BASED IRRIGATION SCHEDULING

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A key ingredient for improving irrigation water management to help conserve water resources is utilizing crop water use information, often referred to as evapotranspiration (ET). This information can be used by growers and their advisers to understand daily crop water use for scheduling irrigations and to determine the amount of water to apply to replenish soil water depletion.

Many resources have been used to develop, promote, and make available ET information for irrigating farmers in Eastern Colorado. Recent survey results suggest that this effort has had some success, but ET-based scheduling has not gained wide acceptance as a primary method for timing irrigations (Figure 1). Rather, a greater number of producers in Eastern reported they use weather station ET as a secondary method of scheduling irrigations, supplemental to

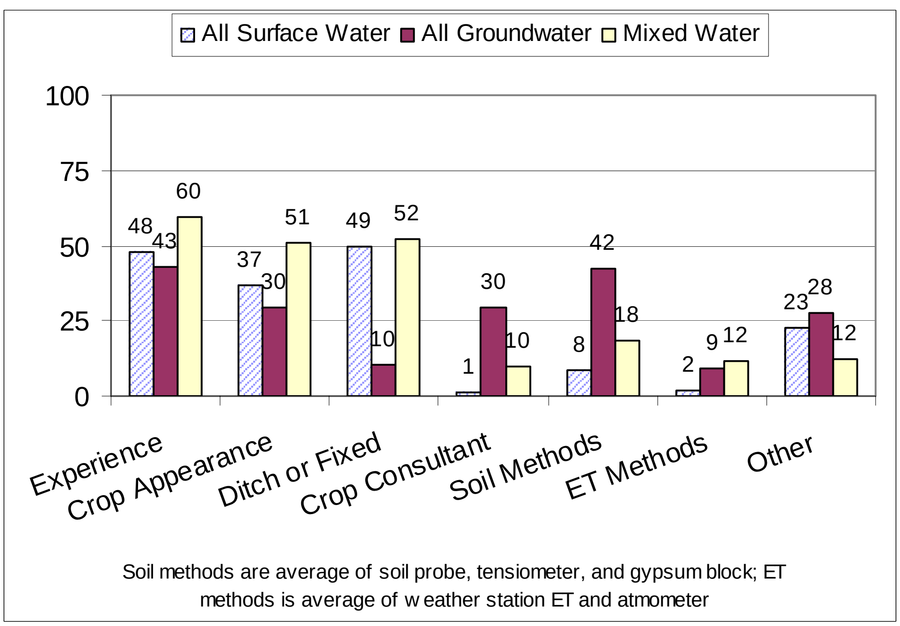

Figure 1. Irrigation scheduling methods chosen by Colorado irrigators in a 2002 mailed survey. Responses are an average of all Colorado regions by primary water source.

other information or methods (Table 1). Likewise, only a minority of growers (seven to nine percent) reported knowing the crop water use of their 2001 irrigated crop in the same survey (Table 2). This suggests that tracking ET through the growing season and scheduling irrigations accordingly is not a frequently used practice. As shown in Figure 1, experience, crop appearance, and ditch or a fixed-day schedule are the most frequently used irrigation scheduling methods used by Colorado irrigators. However, water source (ground or surface water) had a large impact on which methods producers use. These survey results suggest that growers may find ET-based scheduling unattractive and perhaps more work should be done to make ET information more convenient and understandable.

Table 1. Use of ET-related irrigation scheduling methods as found by 2002 Colorado irrigation survey.

	-------- Region --------			
	South Platte	Eastern Plains	Arkansas Valley	Colorado*
	---------- Percent of Respondents Using ---------			
Primary Method				
Crop Consultant	6	34	8	7
Weather Station ET	2	2	3	3
Atmometer	1	0	0	< 1
Computer Program	0	0	0	0
Secondary Method				
Crop Consultant	5	11	6	4
Weather Station ET	16	19	7	12
Atmometer	2	0	1	1
Computer Program	2	0	0	1

*State average includes other regions of the state not shown (n = 1271).

Table 2. Colorado irrigation survey respondents reporting knowledge of crop water use, application amounts and irrigation records (n = 1271).

	---------- Region ----------			
	South Platte	Eastern Plains	Arkansas Valley	Colorado*
	---- Percent (%) of Respondents ----			
Know Crop Water Used (ET)	7	9	7	7
Know Amount of Water Applied	48	63	39	41
Keep Records of Water Applied	21	25	25	23

*State average includes other regions of the state not shown (n = 1271).

Understanding the processes that impact crop ET should help growers and consultants make better use of ET information. Daily ET rates for a given crop depend upon the local weather conditions and the cropping system for which estimates are needed (type of crop, planting date, etc.). Local weather conditions are important because ET is driven by weather factors that determine the drying power of the air. Solar radiation and air temperature provide the energy required to vaporize water. Water vapor loss from the soil or plant is determined by the difference between the water vapor pressure (relative humidity) at the evaporating surface and the surrounding atmosphere. As ET proceeds, the air surrounding the leaf or soil surface becomes gradually saturated and the process will slow down. The ET process might stop if the wet air is not transferred to the atmosphere. The replacement of saturated air close to the plant or soil surface, with drier air from above, explains why wind speed also impacts ET.

With the four weather variables mentioned above; solar radiation, air temperature, humidity, and wind; we can produce a reasonable estimate of daily ET. When measured under a standardized set of conditions, the values obtained from this process provide a measurement of ET that is referred to as reference ET. Reference ET values apply to a specific reference crop grown (usually alfalfa or grass) under a set of local weather conditions. To use reference ET for other crops, we must convert the values using a crop coefficient that provide daily adjustments to the reference ET values generated each day throughout the growing season. In practice, the coefficient is simply a multiplier. The actual daily ET for a given crop on a specific day of the season is the product of the reference ET obtained for that date multiplied by the crop coefficient for that same date. Crop coefficients are sometimes the “weak link” in ET-based irrigation scheduling because they must match the crop growth stage in order to be accurate. Furthermore, coefficients for a few crops in the Great Plains (sunflowers) have not been thoroughly researched and developed.

In order to utilize ET-based scheduling, a reliable source of ET data is required. Colorado has a network of weather stations, called CoAgMet, that provide ET values. CoAgMet is currently accessible on the Internet (www.CoAgMet.com), by an email listserv, and from county Cooperative Extension Offices. CoAgMet provides local reference and crop ET values on a daily basis during the growing season. Currently, the ET reports are calculated using the 1982 Kimberly Penman method. There are crop ET reports for alfalfa, corn, dry beans, small grains, sugar beets, potatoes, and onions. Crop ET reports are also available in a new and original format. The new format for the crop ET reports allows users the ability to select individual stations and crop(s) of interest. Users can also adjust the planting date for a more customized ET estimate. One weakness of the CoAgMet network is that several of the stations are located in areas that are not ideal for reference ET. Therefore, users should investigate stations to see if they are located in a predominately irrigated or dryland area. The CoAgMet network also operates on very limited resources. When station instruments go down during the season, the ability of the network cooperators to provide timely service can be limited.

Table 3. Eastern Colorado CoAgMet stations reporting crop ET.

Station ID	Station Name	Location
ALT01	Ault Station	1 mi SE of Ault
AVN01	Avondale	1 mi SE of Avondale
BRL01	Burlington North*	18 mi NNE of Burlington
BRL02	Burlington No. 2*	6 mi SE Burlington
FTC03	Fort Collins ARDEC	6 mi NE of Fort Collins
FTL01	Fort Lupton	6 mi SSW of Lupton
FTM01	Fort Morgan	8 mi W of Ft Morgan
GLY03	Greeley	2.5 mi NE of Greeley
HLY01	Holly	5 mi NW of Holy
HXT01	Haxtun	2.5 mi NW of Haxtun
HYK02	Holyoke	12 mi SE Holyoke
IDL01	Idalia	2 mi N of Idalia
KRK01	Kirk*	3 mi W of Joes
KSY01	Kersey	2 mi SE of Kersey
LAM02	Lamar #2	7 mi NNE Lamar
PAI01	Paoli*	RD U and 59
PKH01	Peckham	3.5 mi ENE of Peckham
RFD01	CSU Rocky Ford Expt	2.5 mi SE of Rocky Ford
RFD02	Rocky Ford NRCS	2.5 mi SE of Rocky Ford
WRY01	Wray	10 mi N of Wray
YUM02	Yuma #2	2.5 mi N of Yuma

*These stations are located in areas that are predominately non-irrigated. Users should be aware that ET values from these sites will typically be higher (10-15%) than reference ET.

Besides the CoAgMet network in Colorado, there are several other sources of ET information in the tri-state area. In the South Platte Basin of Colorado, the Northern Colorado Water Conservancy District (NCWCD) operates a series of weather stations intended to produce ET reports. Their reports are available on the internet (www.ncwcd.org/, click on Weather/ET Info). These weather stations are generally well maintained and reports are provided for the majority of the area's crops using several different planting dates. Kansas State University provides ET reports from their experiment stations at Colby and Garden City. Evapotranspiration is calculated using a modified Penman equation and the reports are available at: http://www.oznet.ksu.edu/irrigate/. Finally, ET reports in Nebraska are available through the Crop Watch weather site available online at: http://cropwatch.unl.edu/weather.htm. Depending upon the site, ET reports are provided for alfalfa, corn, dry beans, soybeans, sugar beets, potatoes, sorghum and wheat. Estimates are given for daily, 3-day and 7-day averages for three different emergence dates.

Another source of ET information for irrigation scheduling is an atmometer (commercial name ETgage®). This instrument is relatively inexpensive (<$200), simple to use, easy to maintain, and provides an accurate, visual estimate of crop water use. The primary benefit of atmometers is their ability to provide reference ET for the actual location where they are installed. This benefit is particularly useful in areas where there is not a nearby weather station reporting ET.

Atmometers have shown close agreement to Penman method ET in several studies. For example, during the 2003 and 2004 growing season, ETgages with logging capability were installed close (within 15 feet) to the Yuma and Peckham CoAgMet Stations in Northeastern Colorado. Penman Monteith reference ET was calculated using weather data from the CoAgMet weather station and compared to the daily ET values obtained from the ETgages. The average daily difference, either positive or negative, between the weather station ET and the ET provided from the ETgage was less than 0.04 inches per day. This difference decreased as the time interval for calculating the average daily difference decreased from one to seven days (Table 4). This was due to the fact that if the calculated weather ET was higher than the ETgage one day, it was often slightly lower the next day. These results show that a well-placed ETgage can provide a very accurate estimate of reference ET.

Table 4. Reference ET from weather stations compared to auto-logging atmometer ET at two Colorado locations in 2004.

	---------- Yuma -----------		-------- Peckham --------	
Time Period	Regression Coefficient	Average Daily Difference*	Regression Coefficient	Average Daily Difference
	R^2	(inches)	R^2	(inches)
Daily	0.80	0.025	0.86	0.036
2-Day	0.82	0.025	0.91	0.029
3-Day	0.87	0.022	0.89	0.029
5-Day	0.82	0.020	0.92	0.028
7-Day	0.72	0.018	0.93	0.023

*Absolute value of difference between atmometer ET and reference ET

A downside of atmometers is that they only provide reference ET. Therefore, prior to canopy closure and late in the season, crop coefficients (a multiplier) are required to get actual crop ET. However, these can be obtained from tables or estimated by canopy cover fraction to get a reasonable estimate of actual crop ET. Another disadvantage of atmometers is that they do require some maintenance and cannot be allowed to freeze, limiting their use early and late in the growing season.

Regardless of where ET information is obtained, users need to be aware of some potential reasons why a reported ET value may not correctly match the crop ET on their field.

Some potential reasons may include:

1. The weather station site is not similar to the field location. Pay attention to ET from surrounding weather stations as well as the closest station to the field. It may not always be the most representative. Weather conditions can vary over short distances due to topography changes and surrounding vegetation (irrigated vs. dryland).
2. The estimate of crop growth stage for the ET report is different from the actual growth stage for the irrigated field.
3. A wet soil surface prior to full canopy will cause actual crop ET rates to be slightly higher than the ET reports.
4. A dry root zone in the field may cause actual crop ET rates to be lower than the estimated ET.
5. A higher or lower plant population in the irrigated field. A higher population will have higher ET and a lower population will have lower ET in the early and late season. Differences during mid-season disappear as both population densities have sufficient leaf area.
6. Automated weather stations can have instrument failure. Contact the ET provider if you suspect data from a particular station is faulty.

A variety of options exist to help producers and their advisors utilize ET-based irrigation scheduling. Taking advantage of these options may help conserve limited water sources.

IMPROVING IRRIGATION EFFICIENCY

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INTRODUCTION

Declining water supplies, drought, increased competition from other users, and either existing or anticipated restrictions on the amount of water that can be applied over a specified time period, are encouraging many producers to improve the irrigation efficiency of their irrigation systems.

To most people, irrigation efficiency, E_{Irr}, is a general term that indicates how well a water resource is used to produce a crop. Although E_{Irr} can be looked at from several perspectives, this paper deals with it at the field level of a producer. Typically a producer is concerned primarily about making most effective use of water on his farm and does not pay much attention to how individual fields or his farm affects the water budget of an entire watershed. Water that is applied but not beneficially used to produce a crop, is referred to as a loss even though that water may still be physically observed as runoff, etc.

Irrigation efficiency, E_{Irr}, is mathematically defined as:

$$E_{Irr} = Vol_{beneficial} / Vol_{gross}$$

where: $Vol_{beneficial}$ is the volume of water used to produce a crop
Vol_{gross} is the volume of water taken from the water resource

Sometimes the volume of water delivered to a field, $Vol_{delivered}$, is used instead of Vol_{gross}. In situations where there are no significant losses from the water source to the irrigation system such as a center pivot with a well/pump near the pivot, $Vol_{gross} = Vol_{delivered}$. In other situations such as a long, leaky conveyance ditch leading to a field, there are significant losses so that $Vol_{delivered}$ is less than Vol_{gross}. Depending on your perspective or area of interest, it may make sense to include conveyance losses when talking about improving irrigation efficiencies.

Fig. 1 illustrates how the soil water in the root zone varies over time as the evapotranspiration (ET) of the crop withdraws water and periodic irrigations or rains replace water in the root zone. Good water management applies irrigations before the soil moisture level reaches the management allowable depletion (MAD) with an applied depth that just refills the soil profile to field capacity (FC).

The MAD is a management decision of the producer that will vary by crop and his willingness to accept risk of yield reducing stress. If irrigations are too far apart, yielding-reducing water stress will occur. If the applied depth from irrigation or rain causes soil moisture to exceed FC, the excess water either runs off or percolates below the root zone and hence is not beneficially used by the crop.

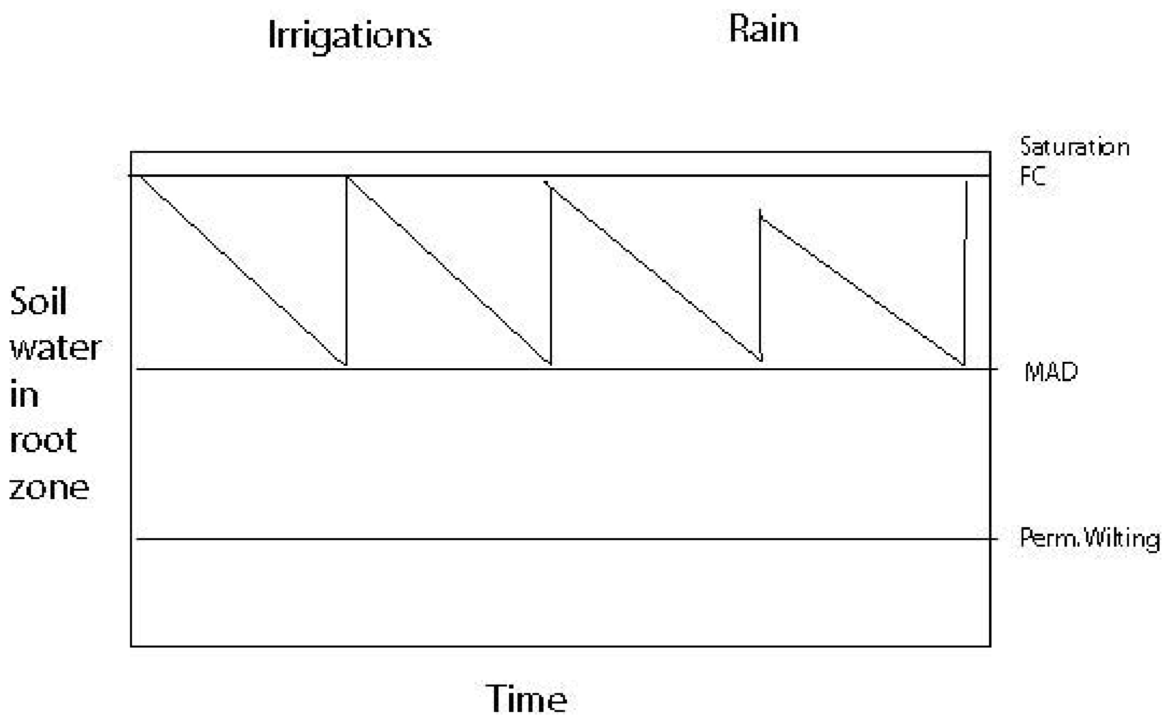

Fig. 1 Schematic of soil water in profile over time

NEED FOR MEASUREWMENTS

It is important to measure the amounts of water beneficially used and delivered to a field in order to document improvements in irrigation efficiency due to management changes and/or upgrades in the irrigation system. Careful measurements of crop water use make it possible to determine the volume of water beneficially used. Other conference papers cover this topic very well.

Accurate measurement of applied water requires properly installed and well maintained equipment. Flumes, such as the Parshall flume, are adequate for open channel flow, unless the headloss through the flume is too great. Another option is to pour a raised concrete sill in an existing concrete ditch. The as-built dimensions can be input into Winflume, an easy-to-use computer program, to create an accurate rating curve for each installation.

Flow meters are typically used for obtaining flow data in the pipelines of pressurized irrigation systems, although other methods can be used. Propeller meters are probably the most common but require periodic maintenance to make sure the propellers turn freely and produce accurate measurements. Ultrasonic flowmeters are non-invasive and very accurate but more expensive. Because they are temporarily attached to the outside of the pipe, they are portable making it possible to measure many irrigation systems with a single piece of equipment. The key to getting accurate measurements from this equipment, is to pay close attention to installation procedures, such as locating the sensors where flows are uniform and the pipe is flowing full.

IMPROVEMENTS TO REDUCE LOSSES

From the definition given above, the closer E_{Irr} is to 1.0, the more efficient is the water use. The most obvious way for increasing E_{Irr} is to reduce losses so Vol_{gross} is as small as possible. A list of possibilities is given below.

1. Significant conveyance losses in an open channel can be reduced by ditch lining, ditch realignment, or installing a closed pipeline.

2. Improve application uniformity to reduce deep percolation

   For surface systems, quicker furrow advance to reduce the differences in infiltration opportunity time along a furrow. Options include land leveling, surge irrigation, furrow firming, etc.

   For sprinkler systems, options include changing sprinkler types, renozzling the system or changing nozzle spacings to improve the overlap between heads.

3. Modify the timing and amount of an irrigation to match the WHC of the soil profile better, thereby reducing percolation and runoff losses.

4. Convert to a more efficient irrigation system (e.g. furrow to sprinkler) to reduce application losses. If the new system is well designed and managed, applications are more uniform reducing deep percolation and runoff.

The implicit assumption is that if a physical change is made in the irrigation system, management also changes appropriately. For example, converting from surface to sprinkler irrigation can greatly reduce water application depths, but if irrigation management does not change as well, then it is still possible to apply as much water as with a surface system.

IMPROVEMENTS TO USE WATER MORE EFFECTIVELY

The previous discussion assumes that available water supply is not limited, so the goal is apply water uniformly at the right time and amount so percolation and runoff are minimal. This may be an ideal situation where the field is managed as a uniform block of soil. The actual situation is likely to be more variable with some water stressed areas where yields are depressed. With the recent interest in adopting new technologies site-specific management of fields, there are additional opportunities for improving E_{Irr} by increasing $Vol_{beneficial}$ in the water stressed areas.

In many irrigated fields, there are significant differences in soil texture that have a large effect on the water holding capacities of the soils. Accurate delineation of these differences is difficult if the only resources available are the USDA-NRCS soil survey and a few soil cores taken across the field. However, recent research has shown that soil texture correlates very well with the bulk electrical conductivity (EC) of soil when the salinity levels are low. The Veris 3100 EC system equipped with global positioning system (GPS) equipment, makes it possible to map the bulk soil EC at a rate of 30-40 ac/hr. Depending on the soil variability, 6 to 12 soil cores are taken, and analyzed for soil texture and other soil properties of interest. The EC values at the sample sites are statistically correlated with the various soil parameters to estimate soil texture and water holding capacity over the entire field. Using this map, the producer can identify the sizes of areas that are of particular concern when he is making management decisions about when and how much water to apply.

Since summer precipitation is generally unpredictable in the western part of the Great Plains, most irrigators do not consider possible rain when they make decisions about irrigation timing and amount. By scheduling irrigations according to the water needs in areas of the field with the lowest water holding capacities, significant water stress affecting yield can be avoided across the entire field.
If water stress affecting yield is detected using remote sensing, yield map from previous year, or some other method, it may be possible to make some changes in the irrigation system or management to reduce the stress and resultant yield reduction in low WHC areas. The course of action with the least cost is to increase the irrigation frequency and decrease the applied depth so the soil water depletion does not exceed the MAD in the low WHC areas. Unless there are very unusual circumstances, the frequency should not be less than 2 days because of the inherent inefficiencies of applying very small depths. Obviously, if adequate water is unavailable because of diminished well yields, management changes cannot increase the available supply. However, if the well yield is sufficient but system capacity is insufficient, redesign with different applicators and/or renozzling the system could increase the available water and reduce stress in the crop.

Obtaining and analyzing a good quality yield map is a good starting point for quantifying the extent and magnitude of yield depressions. Since depressed yields can have various causes, additional information is needed to determine whether irrigation is the primary cause. Aerial images in color and/or infrared wavebands, can be very useful in identifying variability in biomass throughout the season. In-depth field observations are usually very helpful in ground-truthing aerial images.   If there is good evidence that the irrigation regime has caused yield depressions in certain areas of the field, operational changes during an irrigation should be made to best satisfy the irrigation needs over the entire field.

If the available water is limited and water is being applied to minimize water-stressed areas with minimal losses, then increasing $Vol_{beneficial}$ is the only way to improve irrigation efficiency. A clear understanding of what beneficial means is crucial in considering various options. Since a primary objective of irrigation is to optimize crop production for the available water supply, management decisions must consider the how much water is required to achieve at least reasonable economic production. If taken to the extreme where all of the available water supply is applied over a large enough area so there is no percolation or runoff, there could be very little economic production (e.g. no grain production because of severe water stress) even though the irrigation efficiency approaches 1.0. However, a forage crop could be at an economic production level so $Vol_{beneficial}$ is greater than 0, although the optimum balance would probably have more water applied on a smaller area.

This example illustrates two options for management changes that would increase $Vol_{beneficial}$. One possibility is to change the irrigated area so the seasonal application depth would produce an economical production level so $Vol_{beneficial}$ approaches Vol_{gross}.   Another option would be to grow different crops so $Vol_{beneficial}$ could match the available water supply. Although there are a lot of possible scenarios for managing a limited water supply, E_{Irr} will probably be high (near 1.0) and may not change even if the crops grown are changed to produce a larger economic return per unit of water beneficially used. Other conference papers discuss these options in much more detail.

FUTURE

Numerous factors will continue to encourage improvements in on-farm irrigation efficiencies. The trend to convert from surface to pressurized systems will continue, in part at least, to lower labor requirements. Although this conversion enables the producer to apply less water over the season and reduce runoff and deep percolation, there is probably very little reduction in the amount of water used by the crop. The reduction in runoff and percolation translates into fertilizer and chemical savings, has very positive environmental implications, and makes it possible to maintain good production in areas where legal restrictions limit the amount of water that can be withdrawn over time. However, in areas where applied depths are not restricted by law, it is unclear whether there are significant financial benefits from just reducing the amount of water diverted or pumped for irrigation.

CROP RESIDUE AND SOIL WATER EVAPORATION

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Introduction

Sprinkler irrigation can involve frequent wetting of the soil surface. Once to twice per week wetting is common. The largest rates of soil water evaporation occur when the soil surface is wet. At this time soil water evaporation rates are controlled by radiant energy. The more frequently the surface is wet, the more time that the evaporation rates are in the "energy" limited phase. Crop residues have the capacity to modify the radiant energy reaching the soil surface and reduce the soil water evaporation during the "energy" limited phase of evaporation. As the soil surface dries, the evaporation rate is controlled by soil properties. However, with high frequency sprinkler irrigation the soil may remain in the "energy" limited phase. This produces the opportunity for crop residues to impact soil evaporation rates.

Evaporation-Transpiration Partition

Evapotranspiration, consisting of two processes, consumes the water applied by irrigation. The two processes are transpiration soil water evaporation. Transpiration, the process of water evaporating near the leaf and stem surfaces, is a necessary function for plant life. Transpiration rates are related atmospheric conditions and by the crop's growth stage. Daily weather demands cause fluctuations in transpiration as a result. It is literally the process that causes water to flow through plants. It provides evaporative cooling to the plant. Transpiration relates directly to grain yield. As a crop grows, it requires more water on a daily basis until it matures and generally reaches a plateau. Soil water begins to limit transpiration when the soil dries below a threshold which is generally half way between field capacity and wilting point. Irrigation management usually calls for scheduling to avoid water stress. Limited irrigation management requires management to limit plant water stress in critical growth periods and allow more stress during less critical growth periods.

Evaporation from the soil surface may have an effect on transpiration in the influence of humidity in the crop canopy. However, the mechanisms controlling evaporation from soil are independent of transpiration. The combined processes of evaporation from soil (E) and transpiration (T) are measured together as evapotranspiration (ET) for convenience. Independent measurements of E and T are difficult but independent measurements are becoming more important for better water management.

Field research in sprinkler irrigated corn has shown that as much as 30% of total evapotranspiration is consumed as evaporation from the soil surface (Klocke et. al., 1985). These results were from bare surface conditions for sandy soils. For a corn crop with total ET of 30 inches, 9 inches would be going to soil evaporation and 21 inches to transpiration. This indicates a window of opportunity if the unproductive soil evaporation component of ET can be reduced without reducing transpiration.

Evaporation from Soil Trends

Evaporation from the soil surface after irrigation or rainfall is controlled first by the atmospheric conditions and by the shading of a crop canopy if applicable. Water near the surface readily evaporates and does so at a rate that is only limited by the energy available. This so-called energy limited evaporation lasts as long as a certain amount of water that evaporates, 0.47 inches for sandy soils and 0.4 inches for silt loam soils. The time it takes to reach the energy limited evaporation depends on the energy available from the environment. Bare soil with no crop canopy on a sunny hot day with wind receives much more energy than a mulched soil under a crop canopy on a cloudy cool day with no wind.

After the threshold between energy limited and soil limited evaporation is reached, evaporation is controlled by how fast water and water vapor can move through the soil to the soil surface. There is a diminishing rate of evaporation with time as the soil surface dries. The soil surface insulates itself from drying as it takes longer for water or vapor to move through the soil to the surface.

The challenge for sprinkler irrigation is the high frequency that the soil surface is put into energy limited evaporation. With twice-weekly irrigation events it is likely that the soil surface will be in the higher rates of energy limited evaporation during the entire growing season. Only during the early growing season with infrequent irrigations and little canopy development would there be a possibility for lower rates of soil limited evaporation.

Evaporation and Crop Residues

For many years, crop residues in dryland cropping systems have been credited for suppressing evaporation from soil surfaces. Evaporation research dates back into the 1930’s when Russel reported on work with small canister type lysimeters (Russel, 1939). Stubble mulch tillage and Ecofallow have followed in the progression of innovations with tillage equipment, planting equipment, and herbicides to allow for crop residues to be left on the ground surface. These crop residue management practices along with crop rotations have increased grain production in the Central Plains. Water savings from soil evaporation suppression has been an essential element. In dryland management, saving 2 inches of water during the fallow period from wheat harvest until planting corn the next spring was important because in meant an increase of 20 to 25 bushels per acre in the corn crop. This difference came from the presence of standing wheat stubble during the fallow period versus bare ground.

North Platte, Ne Study

The question is to what extent water savings could be realized from crop residue management in sprinkler irrigation? A research project (Todd et al., 1991) was conducted near North Platte, NE during the mid 1980's to begin to address this question. Four canister type lysimeters were placed across the inter-row of sprinkler irrigated corn. The lysimeters were 6 inches in diameter and 8 inches deep and were filled by pressing the outer wall into the soil. The bottoms were sealed and the lysimeters were weighed daily to obtain daily evaporation from changes in daily weights.

Half of the lysimeter treatments were bare soil and half were covered with flat wheat straw mulch at the rate of 6000 pounds/acre or the equivalent to the straw produced from a 60 bu/acre wheat crop. The other variable was irrigation frequency: dryland, limited irrigation, and full irrigation. The sprinkler irrigation system was a solid set equipped with low angle impact heads on a grid spacing of 40 ft X 40 ft. The corn population varied with the irrigation variable and was appropriate with the expected water application and yield goal for that treatment. The resulting leaf area, shading, and biomass followed accordingly.

The results are summarized in Tables 1 and 2. Evaporation measurements with the mini-lysimeters were not taken during days of irrigation or rainfall. Data were collected from June 10 to September 13 in 1986 with 78, 75, and 75 days of collection from dryland, limited irrigation, and full irrigation, respectively. In 1987, data were collected from May 28 to August 20 with 65, 64, and 59 days of collection, for dryland, limited irrigation, and full irrigation, respectively.

To understand the possible full season implications of this study, the average daily evaporation rates were applied to the missing days of data during the respective time periods. These evaporation values may still be conservative since evaporation rates are highest immediately after wetting (Table 1).

Only six rainfall events were more than 0.4 inch of precipitation. After these significant rainfall events occurred, the bare soil in the dryland treatment showed brief periods of energy limited evaporation. When the straw covered and bare soil dry land treatments were paired together, they had nearly the same evaporation both with and without the crop canopy. This implied that the crop canopy had some effect on evaporation, but the wheat straw did not for dryland management. Soil limited evaporation was more of the controlling factor.

The limited irrigation added three irrigation events of, 2.0, 2.0, and 1.75 inch. The cumulative evaporation for bare soil unshaded treatment showed the classic patterns of energy limited-soil limited evaporation. These patterns were suppressed in the other treatments indicating that the canopy and residue prolonged the transition from energy limiting to soil limiting evaporation. During the last 40 days of the season, the mulched unshaded treatment and bare treatment under the canopy closely tracked one another and ended with similar cumulative evaporation. The singular contribution of the straw mulch and crop canopy, each acting alone, were the same. However, in limited irrigation straw mulch added a benefit to the canopy effect that was not evident in dryland management. The reduction in evaporation by the straw compared with the bare soil was more under the canopy than without the canopy. The straw mulch contributed to reducing energy limited evaporation more days under the canopy than in the unshaded treatment. The evaporation probably shifted from energy to soil limited sooner after wetting in the unshaded than the canopy treatment.

Full irrigation included nine irrigation events, seven of which were at weekly intervals and two that were at two-week intervals. The pattern of cumulative evaporation from the unshaded bare soil treatment indicated periods of both energy and soil limited evaporation. These patterns were more subtle early in the bare soil treatment under the crop canopy. The magnitude of unshaded bare soil evaporation was larger in the fully irrigated treatment, but the unshaded mulched and bare soil evaporation under the canopy was similar to the limited values. These latter two treatments also tracked each other closely as they did in they limited management. The reduction in evaporation from the wheat stubble was even more in the fully irrigated management than the limited and dryland management. This effect started early and carried on throughout the growing season.

Table 1. Projected growing season soil water evaporation including irrigation and rainfall days. (Klocke, 2004)

	---Unshaded----		Corn Canopy---	
Year	Bare	Straw	Bare	Straw
	-------------------in/season--------------			
	------------------Dryland-----------------			
1986	7.6	7.6	5.2	5.2
1987	8	7.1	6.1	5.7
	------------Limited Irrigation----------			
1986	10.4	8.5	7.6	5.2
1987	11.3	9.4	8.5	5.7
	------------Full Irrigation---------------			
1986	15.1	8.5	7.6	3.8
1987	14.6	9.4	8.5	4.7

*North Platte, NE

Table 2. Full season soil water evaporation savings from straw cover compared with bare soil. (Klocke, 2004).

Year	---Unshaded----	Corn Canopy--
	----------------in/season----------------	
	--------------------Dryland--------------	
1986	0	0
1987	0.9	0.4
	------------Limited Irrigation----------	
1986	1.9	2.4
1987	1.9	2.8
	---------------Full Irrigation------------	
1986	6.6	3.8
1987	5.2	3.8

*North Platte, NE

Garden City, KS Study

A similar study was conducted in Garden City, Kansas during 2004 in soybean and corn canopies. Two twelve inch diameter PVC cylinders that held 6-inch deep soil cores were placed between adjacent soybean or corn rows. The crop rows were spaced 30 inches apart. These mini-lysimeters, which had been cored into natural field settings, were either bare or covered with corn stover or standing wheat stubble. The treatments were replicated four times in plots that were irrigated once or twice weekly.

Soil water evaporation measurements began on June 2 and June 9 for corn and soybean, respectively. The early season measurements were taken in an unshaded location out of the field setting and continued until June 30 and July 13 for corn and soybean, respectively. At these times, the lysimeters measurements were initiated in the field. Soil water evaporation measurements were recorded on 60 of 83 days between June 30 and September 20 for the corn canopy and 51 of 70 days between July 13 and September 20 for soybeans. The missing days were due to rainfall and irrigation. Average daily evaporation from measured data during vegetative and full canopy growth periods were used to fill the data gaps.

Growing season irrigation and rainfall event totals are in Table 3. The irrigation amounts for fully watered corn and soybean were approximately half of normal. Rainfall was above normal and timely and the soil profile was filled at the beginning of the season.

Table 3. Growing season irrigation and rainfall events and accumulation for Garden City site during 2004.

	----Soybean----		-----Corn---------	
	Events	Inches	Events	inches
Once/Week	3	3	4	4
Twice/Week	7	7	9	9
Rain	23	12.8	24	14.3

Results in Table 4 are the total evaporation amounts for the growing season and the percentages of evapotranspiration (ET). The development of the crop canopy affected evaporation rates as the season progressed. Evaporation rates and E as percentage of ET decreased as the canopy developed (data not shown).

The results in Table 5 give the same possibilities for reductions in evaporation as the results from the previous Nebraska corn study. Also, the roles of corn stover and standing wheat straw are shown. The corn stover in the lysimeters covered 87% of the soil surface, which is equivalent to very good no-till residue cover. These results reflect the maximum capability of the residue for evaporation suppression.

Table 4. Projected growing season (2004) soil water evaporation from soybean and corn crops with bare soil, corn stover, and wheat stubble surface treatments.

	-------Soybean-------		---------Corn-----------	
	----June 9-Sept. 20-		----June 2-Sept. 20-	
Cover*	Soil E --inches--	% of ET	Soil E --inches--	% of ET
Bare 1	6.50	33	5.78	32
Bare 2	7.90	32	6.59	35
Corn 1	3.80	19	3.10	17
Corn 2	3.66	15	3.77	19
Wheat1	3.37	17	2.72	15
Wheat2	4.07	17	3.74	19

*****1=weekly and 2=twice weekly irrigation frequency

Table 5. Growing season (2004) soil water evaporation savings with corn stover and wheat stubble compared with bare soil.

	-------Soybean--------	---------Corn----------
	----June 9-Sept. 20--	----June 2-Sept. 20-
Cover*	Soil E --inches--	Soil E --inches--
Corn 1	2.70	2.68
Corn 2	4.24	2.82
Wheat1	3.13	3.06
Wheat2	3.83	2.85

*****1=weekly and 2=twice weekly irrigation frequency.

Summary

No matter how efficient sprinkler irrigation applications become, the soil is left wet and subject to evaporation. Frequent irrigations and shading by the crop leave the soil surface in the state of energy limited evaporation for a large part of the growing season. Research has demonstrated that evaporation from the soil surface is a substantial portion of total consumptive use (ET). These measurements have been 30% of ET for E during the irrigation season for corn on sandy and silt loam soils. It has also been demonstrated that crop residues can reduce the evaporation from soil in half even beneath an irrigated crop canopy. The goal is to reduce the energy reaching the evaporating surface.

We may be talking about seemingly small increments of water savings in the case of crop residues. The data presented here suggests the potential for a 2.5 to 3.5 inch water savings due to the wheat straw during the growing season. Dryland research would suggest that stubble is worth at least 2 inches of water savings in the non growing season. In water short areas or areas where water allocations are below full irrigation, 5 inches of water translates into possibly 20 and 60 bushels per acre of soybean and corn, respectively.

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CROP RESIDUE AND SOIL WATER

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INTRODUCTION

Final crop yield is greatly influenced by the amount of water that moves from the soil, through the plant, and out into the atmosphere (transpiration). Generally, the more water that is in the soil and available for transpiration, the greater the yield. For example, dryland wheat yield is strongly tied to the amount of soil water available at wheat planting time (Fig. 1). In this case an additional inch of water stored in the soil at wheat planting time would increase yield by 5.3 bu/a. For wheat selling at $3.21/bu, that inch of stored soil water is worth $17/a. Similar relationships can be defined for other crops. But the point is that in the Great Plains where precipitation is low and erratic, an important production factor is storing as much of the precipitation and irrigation that hits the soil surface as possible.

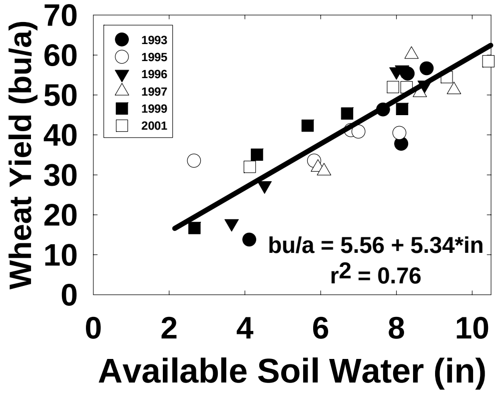

Fig. 1. Relationship between winter wheat grain yield and available soil water at wheat planting at Akron, CO.

FACTORS AFFECTING WATER STORAGE

Time of Year/Soil Water Content

The amount of precipitation that finally is stored in the soil is determined by the precipitation storage efficiency (PSE). PSE can vary with time of year and the water content of the soil surface. During the summer months air temperature is very warm, with evaporation of precipitation occurring quickly before the water can move below the soil surface. Farahani et al. (1998) showed that precipitation storage efficiency during the 2 ½ months (July 1 to Sept 15) following wheat harvest averaged 9%, and increased to 66% over the fall, winter, and spring period (Sept 16 to April 30) (Fig. 2). The higher PSE during the fall, winter, and spring is due to cooler temperatures, shorter days, and snow catch by crop residue. From May 1 to Sept 15, the second summerfallow period, precipitation storage efficiency averaged -13% as water that had been previously stored was actually lost from the soil. The soil surface is wetter during the second summerfallow period, slowing infiltration rate, and increasing the potential for water loss by evaporation.

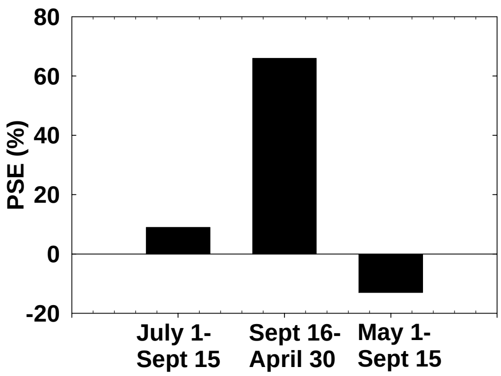

Fig. 2. Precipitation Storage Efficiency (PSE) variability with time of year. (after Farahani, 1998)

Residue Mass and Orientation

Studies conducted in Sidney, MT, Akron, CO, and North Platte, NE (Fig. 3) demonstrated the effect of increasing amount of wheat residue on the precipitation storage efficiency over the 14-month fallow period between wheat crops.

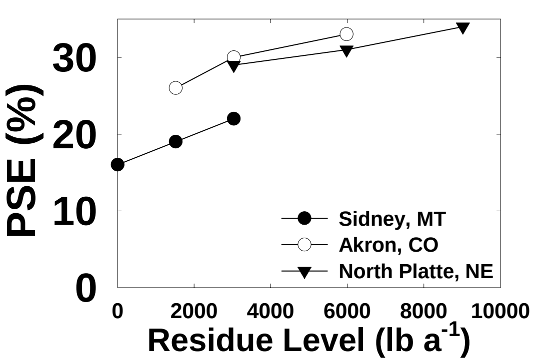

Fig. 3. Precipitation Storage Efficiency (PSE) as influenced by wheat residue on the soil surface. (after Greb et al., 1967)

As wheat residue on the soil surface increased from 0 to 9000 lb/a, precipitation storage efficiency increased from 15% to 35%. Crop residues reduce soil water evaporation by shading the soil surface and reducing convective exchange of water vapor at the soil-atmosphere interface. Additionally, reducing tillage and maintaining surface residues reduce precipitation runoff, increase infiltration, and minimize the number of times moist soil is brought to the surface, thereby increasing precipitation storage efficiency (Fig. 4).

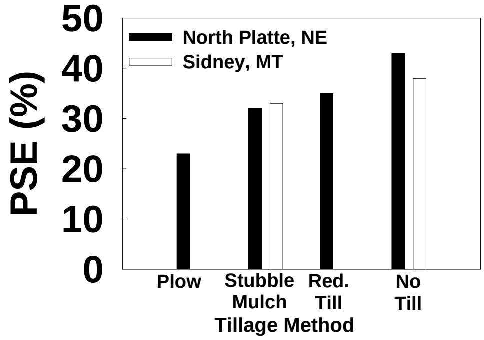

Fig. 4. Precipitation Storage Efficiency (PSE) as influenced by tillage method in the 14-month fallow period in a winter wheat-fallow production system. (after Smika and Wicks, 1968; Tanaka and Aase, 1987)

Snowfall is an important fraction of the total precipitation falling in the central Great Plains, and residue needs to be managed in order to harvest this valuable resource. Snowfall amounts range from about 16 inches per season in southwest Kansas to 42 inches per season in the Nebraska panhandle. Akron, CO averages 12 snow events per season, with three of those being blizzards. Those 12 snow storms deposit 32 inches of snow with an average water content of 12%, amounting to 3.8 inches of water. Snowfall in this area is extremely efficient at recharging the soil water profile due in large part to the fact that 73% of the water received as snow falls during non-frozen soil conditions.

Standing crop residues increase snow deposition during the overwinter period. Reduction in wind speed within the standing crop residue allows snow to drop out of the moving air stream. The greater silhouette area index (SAI) through which the wind must pass, the greater the snow deposition (SAI = height*diameter*number of stalks per unit ground area). Data from sunflower plots at Akron, CO showed a linear increase in soil water from snow as SAI increased in years with average or above average snowfall and number of blizzards. Typical values of SAI for sunflower stalks (0.03 to 0.05) result in an overwinter soil water increase of about 4 to 5 inches (Fig. 5).

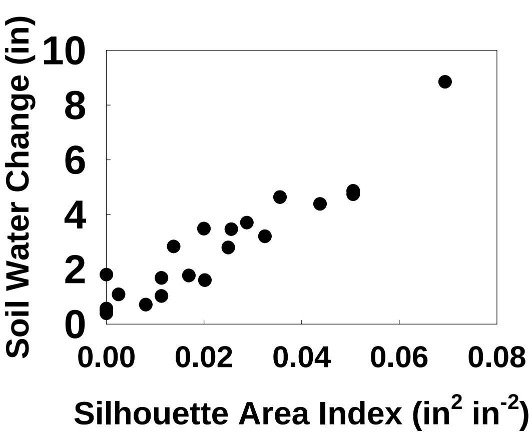

Fig. 5. Influence of sunflower silhouette area index on over-winter soil water change at Akron, CO. (after Nielsen, 1998)

Because crop residues differ in orientation and amount, causing differences in evaporation suppression and snow catch, we see differences in the amount of soil water recharge that occurs (Fig. 6). The 5-year average soil water recharge occurring over the fall, winter, and spring period in a crop rotation experiment at Akron, CO shows 4.6 inches of recharge in no-till wheat residue, and only 2.5 inches of recharge in conventionally tilled wheat residue. Corn residue is nearly as effective as no-till wheat residue in recharging soil water, while millet residue gives results similar to conventionally tilled wheat residue.

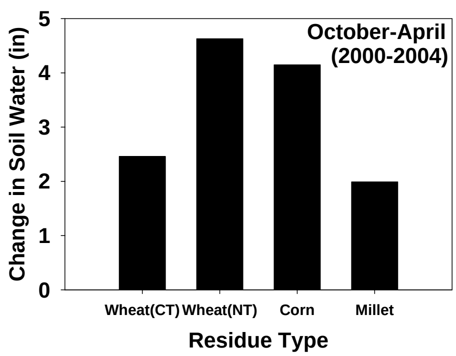

Fig. 6. Change in soil water content due to crop residue type at Akron, CO.

Good residue management through no-till or reduced-till systems will result in increased soil water availability at planting. This additional available water will increase yield in both dryland and limited irrigation systems by reducing level of water stress a plant experiences as it enters the critical reproductive growth stage.

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DRIP AND EVAPORATION

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ABSTRACT

Loss of water from the soil profile through evaporation from the soil surface is an important contributor to inefficiency in irrigated crop production. Residue management systems may reduce this evaporative loss, but cannot be used in all cropping systems. Choice of the irrigation system and its management also can reduce evaporative loss. In particular, subsurface drip irrigation limits soil surface wetting and can lead to an overall reduction in evapotranspiration (crop water use) of as much as 10%. The example presented shows that most of the water savings occur early in the season when crop cover is not yet complete. Because evaporation from the soil surface has a cooling effect on the soil in the root zone, irrigation methods that limit evaporation will result in smaller fluctuations in soil temperature and warmer soil temperatures overall. For some crops such as cotton, this has beneficial effects that include earlier root growth, better plant development and larger yields.

PREVIOUS STUDIES

Crops grown under subsurface drip irrigation may out yield those grown under surface drip (Phene et al., 1987) or use less water for the same yield (Camp et al., 1989). Yield differences may be related to differences in plant available water due to greater evaporation from the soil surface with surface irrigation. However for corn (Zea mays) grown in 1993 on the Pullman clay loam at Bushland, TX, there was no significant yield difference for well-watered treatments (Howell, et al., 1997).

Tarantino et al. (1982) compared microclimate and evapotranspiration (ET) of tomatoes under surface drip and furrow irrigation on weighing lysimeters and found no difference in seasonal ET when canopy development was similar. Drip irrigation was daily in their study while furrow irrigation frequency was about 10 d. The higher ET from furrow irrigation for the 3 d after irrigation was offset by the generally higher ET from drip irrigation on other days due to the continuously wetted soil surface under drip. Even though the loam soil surface was only partially wetted, advection from dry, hot inter-row areas contributed to the energy available to drive evaporation from the wet surface. If soil surface wetting could have been reduced by using subsurface drip, the ET from drip irrigation might well have been lower than that under furrow irrigation. When drip and sprinkler irrigations were both daily on a sandy soil, net radiation and ET were larger for sprinkler irrigation compared to drip irrigation of tomatoes (Ben-Asher et al., 1978).

Bordovsky et al. (1998) compared LEPA and SDI irrigation of cotton at application rates of 0.1, 0.2, and 0.3 inches per day. Lint yields of 1145, 1225, and 1259 lb/acre for SDI were all larger than the yields of 980, 1142, and 1187 lb/acre under LEPA. The yield decrease with LEPA was attributed to larger evaporative losses. Spacing of LEPA drops and SDI laterals was identical; but SDI laterals were buried at 12-inch depth. Emitter spacing was 24 inches and flow rate was 0.336 gal/hr.

Computer Modeling Efforts

Drip irrigation using buried emitters has the potential to save irrigation water by reducing soil surface wetting and thus reducing evaporation (E). However, measurement of evapotranspiration (ET) for different combinations of emitter depth and cropping systems is very difficult and time consuming, in part because of non-uniform soil surface wetting (Matthias et al., 1986). Thus, computer simulations are important tools for looking at ET differences for different irrigation practices. Water flow during microirrigation has been variously simulated as essentially one-dimensional (Van Bavel et al., 1973), two-dimensional axisymmetric (Brandt et al., 1971; Nassehzadeh-Tabrizi et al., 1977), and two-dimensional rectilinear (Ghali and Svehlik, 1988; Oron, 1981). Lafolie et al. (1989) introduced both axisymmetric and rectilinear finite difference solutions. Although some of these studies included root uptake, none of them attempted to model the energy and water balances of the crop canopy and soil surface.

Recognizing the inability of existing models to simulate the differences in crop ET due to dripline depth, Evett et al. (1995) modified a mechanistic ET model, ENWATBAL, to simulate irrigation with drip emitters at any depth. They used the model to simulate energy and water balance components for corn (Zea mays L., cv. PIO 3245) grown on the Pullman clay loam soil at Bushland, TX using emitters at the surface and at 0.15- and 0.30-m depths (6 and 12 inches). Data were from an actual corn crop grown with drip irrigation. Irrigation was daily and was scheduled to replace crop water use as measured in the field by neutron scattering (Fig. 1).

Modeled transpiration (T) was essentially equal for all emitter depths [428 mm (16.9 inches) over 114 days from emergence to well past maximum leaf area index (LAI)]. But, loss of water to evaporation (E) was 2 inches (51 mm) and 3.2 inches (81 mm) less for 6- and 12-inch deep (0.15- and 0.30-m) deep emitters, respectively, compared with surface emitters (Fig. 2). This is about the same as the range of water savings predicted by Bonachela et al. (2001) when converting from surface irrigation to buried drip irrigation on a sandy loam soil in Spain.

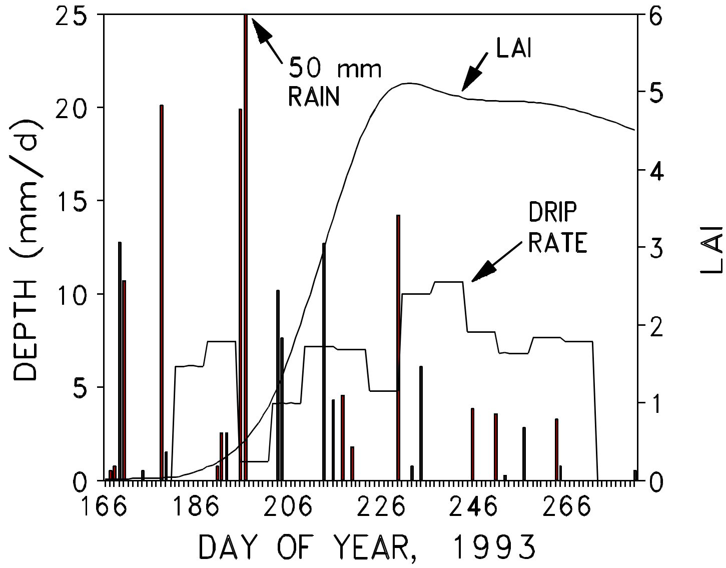

Figure 1. Depth of rainfall (25 mm is 1 inch) and drip irrigation for each day of the corn growing season. Also plotted is the crop leaf area index, which peaked in mid August. A 2-inch (50-mm) rain goes off the plot scale.

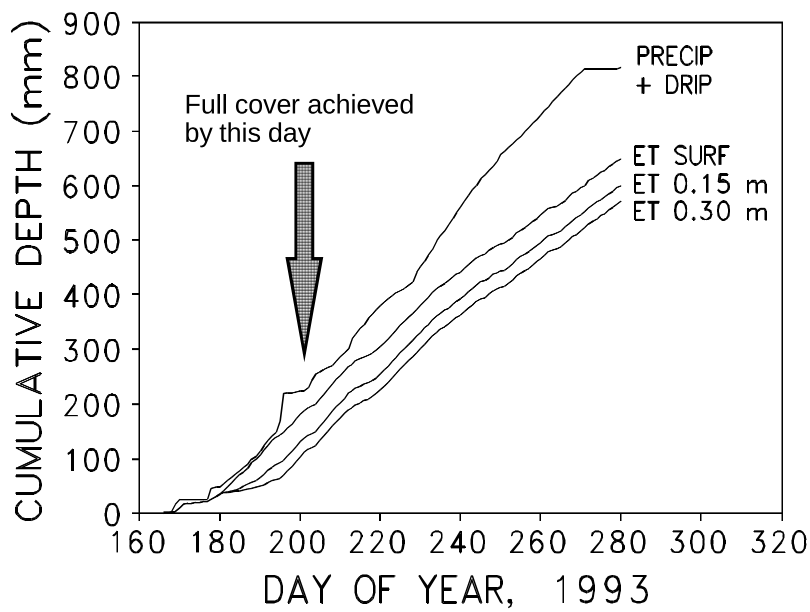

Figure 2. Cumulative depth of crop water use (ET) during the corn growing season for drip irrigation with dripline on the surface (SURF), dripline at 6-inch depth (ET 0.15 m), and dripline at 12-inch depth (ET 0.30 m). For comparison, the cumulative amount of precipitation plus drip irrigation since planting is also plotted. The difference between cumulative precipitation plus irrigation and the ET values is due to filling of the soil profile over the season, plus some drainage losses. One inch is 25.4 mm. Seasonal ET for drip irrigation with surface dripline was 25.6 inches.

For surface emitters, net radiation was much greater and sensible heat flux was smaller than for subsurface emitters until LAI increased past 4.2 mid-way through the season. Thus, almost all of the differences in ET occurred during the period of partial canopy cover (Fig. 2). Differences in energy balance components between treatments were minor after day of year 220 (early August). The study showed that water savings of up to 10% of seasonal precipitation plus irrigation could be achieved using 30-cm (12-inch) deep emitters under these soil and climatic conditions.

Predicted drainage was slight, ranging from 0.25 to 0.5 inch [6-, 8- and 12-mm for surface, and 6- and 12-inch (0.15- and 0.30-m) deep emitters, respectively], but comparisons of predicted and measured soil water profiles at season's end showed that deep drainage of more than 6 inches (150 mm) of water may have occurred. There were minor differences in soil heat flux between the treatments because soil heat flux was a relatively minor component of the energy balance.

The decrease in evaporative losses predicted by this computer model is supported by analytical solutions derived by Lomen and Warrick (1978) and Philip (1991). However, Philip (1991) pointed out that deep percolation losses potentially could increase as drip irrigation depth increases.

Evaporation and Soil Temperature

Rapid decreases in soil temperature, such as those often accompanying furrow or sprinkler irrigation, result in decreased plant transpiration (Ali et al., 1996). Since transpiration and yield are directly and positively related, this would translate into a decrease in yield. Comparative study has shown that subsurface drip irrigation at 10-inch depth (25 cm) resulted in warmer soil temperatures throughout the root zone when compared with furrow irrigation (Bell et al., 1998). Also, the daily range of temperature was smaller with SDI. These effects were associated with a decrease in lettuce disease (Bell et al., 1998). There is anecdotal evidence in the southern High Plains that drip irrigation of cotton results in improved yields due to warmer soil temperatures. Colaizzi et al. (2004b) found warmer soil temperatures with SDI than with LESA and LEPA sprinkler irrigation of cotton. This supports results of the modeling effort of Evett et al. (1995), which also predicted warmer soils with SDI compared with surface irrigation.

Cotton rooting is greatly decreased by cool soil temperatures. So there is a competitive advantage to managing for warmer soil temperatures earlier in the season. Some cropping systems employ plastic mulch to improve soil warming in the spring. This practice is common in the cooler regions of Uzbekistan, the cotton producing capitol of Central Asia. Comparative studies of SDI vs. furrow irrigation of cotton in Uzbekistan showed that cotton yield under drip irrigation was 22% greater than under furrow irrigation and that water use efficiency was 76 to 103% greater with drip (without plastic mulch) (Kamilov et al., 2003). There is some promise that SDI can provide similar advantages for cotton production on the southern Great Plains.

RECOMMENDATIONS

Subsurface drip irrigation will reduce losses to evaporation from the soil surface compared with furrow irrigation. The savings will increase as the wetted area on the soil surface decreases. Thus, wider dripline spacings and deeper burial will improve the water savings. With system designs that are commonly in use, the water savings may range from 1 to 3 inches per season. The economic impact of this savings will vary with the cost of water (primarily pumping costs) and the rate of return per inch of water. In a situation where water is plentiful and irrigation scheduling is managed for maximum yield, the increase in yield per inch of water may be non-existant. However, in the more common situation where the irrigation supply is less than the crop would use for maximum yield, we are in a deficit irrigation situation. In the deficit irrigation realm, the increase in yield per inch of water is usually near the maximum for a given crop. This is one reason why Colaizzi et al. (2004a,b) found greater sorghum and cotton yields under deficit irrigation regimes with SDI than with LEPA or spray sprinkler irrigation at Bushland, Texas. In the deficit irrigation regimes they studied, the increase of cotton yield was 86 pounds of lint per acre-inch of water, and the increase of sorghum yield was 232 pounds per acre-inch. At $0.40 per pound for cotton and $2.00 per bushel for sorghum, the 1 to 3 inch range of water savings represents marginal income increases ranging from $34 to $103 dollars per acre for cotton and from $7.70 to $23 for sorghum. Bhattarai et al. (2003) found similar trends for cotton grown under drip and furrow irrigation in Australia. Their dripline was buried at 16-inch depth and spaced at 40 inches. Yield for SDI at 75% of full ET was as large as that of furrow irrigation at 100% of full ET, and water use efficiency was larger for SDI.

Many other factors influence the decision to use SDI. For instance, deep percolation losses may increase with depth of dripline burial, depending on the soil layering and rooting pattern. Also, germination may be difficult in dry years, again depending on the soil, if dripline is buried too deeply and is spaced too far from the plant row. But, if water is short and the crop is sensitive to cool soil, then SDI can deliver with water savings and warmer soil temperatures.

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WATER MANAGEMENT
FOR SUGARBEET AND DRY BEAN

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The past several years of sustained drought and expectations for below average snowpack and summer rains have many in agriculture searching for ways to stretch limited supplies of water. Not only has stream flow decreased, but ground water levels have declined and in many areas pumping restrictions have been imposed. At the same time, competition for water outside of agriculture further increases the demand for limited resources. The combination of drought and the increased demand for water will impose even more challenges for irrigated agriculture. It will require changing current irrigation practices and incorporation of new ideas to better utilize available water supplies as efficiently as possible. This means not only using irrigation water efficiently, but also using precipitation and stored soil water for crop production. Understanding the water needs of a crop will be a key to effective water management.

Water Use
The amount of water needed for irrigation varies by the crop being grown and the climatic conditions from year to year. Given in Table 1 are estimated water use rates for regionally grown crops.

Alfalfa	Corn	Drybean	Spring Grain	Soybean	Sunflower	Sugarbeet	Winter Grain
31-33	23-26	15-16	18-20	18-20	18-26	23-25	18-22

Table 1. Seasonal crop water use (in.) for regionally grown crops.

The depth from which sugarbeets get most of their water is generally considered to be from the top 3 to 4 ft of the soil profile. Sugarbeets use approximately 24 inches of water during the growing season and are often considered a crop that uses a large amount of water. Yet as we look closer, some of the crops we thought used less water, for example sunflowers and winter wheat, we find can use as much water as sugarbeets. However in the case of sunflowers and winter wheat, these crops can extract more water from the profile than most crops without adversely impacting yield potential. Sunflowers also have the ability to effectively extract water to depths of up to eight feet. In this case sunflowers may be viewed as a “drought tolerant” crop when in fact the crop has actually extracted more water from the soil and extracted water from deeper in the soil profile. Anyone growing sunflowers knows that following this crop the soil can be left in a very dry condition the following spring.

Dry beans use approximately 16 inches of water during the growing season, which is approximately 8 inches less than what corn needs. This makes dry beans a good crop to grow if irrigation water is limited or if used as part of a crop rotation system to reduce overall irrigation needs. Dry beans are a shallow rooted crop with the majority of roots found in the top 18 in. of the soil profile. Roots can grow deeper into the soil profile to get water but this usually occurs late in the growing season as the plants begin to mature.

Water Management

The question of when is the best time to apply water to a crop often comes up when water supplies are limited. Some producers feel that stressing dry beans early in the growing season has little impact on yield and may even improve yield by forcing the roots to grow deeper into the soil profile. A similar question asked at the end of the season is whether stopping irrigation late in the season reduces yield?

For dry beans, early and late season water stress experiments have been conducted at the Panhandle Research and Extension Center in Scottsbluff, NE. The results of those experiments are given below.

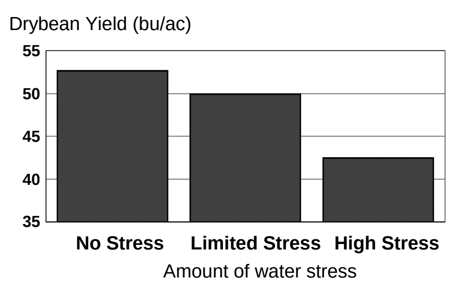

Figure 1a. Effect of early season water stress on dry bean yield using sprinkler irrigation.

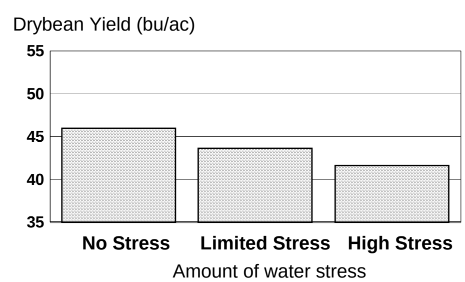

Figure 1b. Effect of early season water stress on dry bean yield using furrow irrigation.

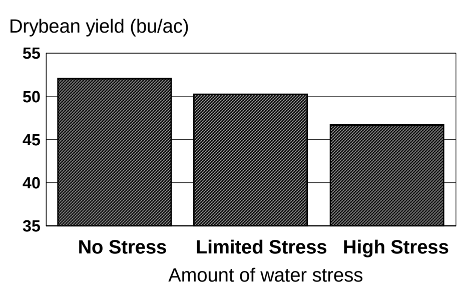

Figure 2a. Effect of late season water stress on dry bean yield using sprinkler irrigation.

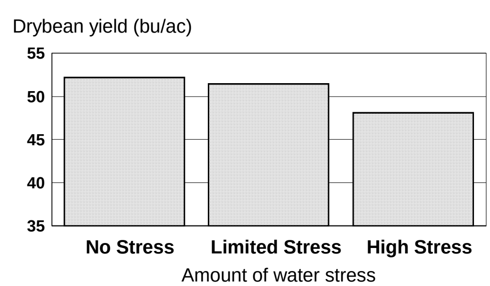

Figure 2b. Effect of late season water stress on dry bean yield using furrow irrigation

Figures 1a and 1b, show the results of dry bean yield when water is limited during early season growth for sprinkler and furrow irrigation systems, respectively. The no stress treatment had irrigation starting approximately the last week in June to the first week in July. For the limited and high stress treatments, the initial irrigation was delayed for one week and two weeks, respectively. When sprinkler irrigation was used, yield tended to decline more as water stress increased compared to the furrow irrigation system. This is especially true for the high stress treatment under sprinkler. Yield loss was greater when water was withheld for two weeks because of the inability of the sprinkler system to replace soil water and meet the future water demand of the crop. A furrow irrigation system tends to refill the soil profile and is thus able to provide adequate water for future water use.

In figures 2a and 2b, the results of shutting off water late in the season are also shown for both sprinkler and furrow irrigation systems. The no stress treatment had irrigations throughout the growing season. Starting August 10, the limited stress treatment received every other irrigation that was scheduled for the no stress treatment while the high stress treatment received no further irrigations. Similar to the early season water stress results, dry beans irrigated with a sprinkler system showed a slightly steeper decline in yield as water stressed increased. The decline in yield is again likely related to the inability of the sprinkler irrigation system to supply water in excess to the requirements of the crop. Once irrigation was reduced or stopped less water was available in the soil profile to meet crop demands.

When comparing the early and late season experiments, there is a steeper decline in dry bean yield when water stress occurs at the beginning of the season as compared to water stress late in the season. These results are probably not uncommon and could be expected for most crops. Early in the season plant root development is limited and therefore water stress can occur rapidly. The lack of water during initial stages of plant growth likely impacts the majority of the root system. Late in the growing season, roots are more developed and reach further into the soil profile. Therefore water stress late in the season will first impact roots high in the soil profile while those deep in the profile may continue to extract some water to meet the needs of the crop. Finally, because the plant is nearing maturity, the need for water is declining on a daily basis and the root system can more easily keep up with the needs of the plant as water in the profile slowly moves to replace the water used by the crop.

For sugarbeets, the most critical time period when irrigation can affect final yield is during germination and early plant development. Inadequate soil water for germination and emergence results in reduced plant populations which in turn reduce final yield. Water stress after plants have emerged can result in seedling desiccation. At the early growth stages when root development is minimal, water stress can result in plant death with only a few days of warm dry winds. Often times if soil water is not adequate and stress begins, it is difficult to replenish the soil water in a timely fashion. Even with center pivot irrigation, adequate water must be applied otherwise a light application merely meets the days evaporation demand. It is important to have an adequate supply of water in the soil below the seedling which allows soil water to migrate upwards and meet demands of the young seedling. As the season progresses, adequate water should be available to allow the sugarbeet to develop a good root system for extracting water from the soil.

The impact of late season water stress on sugarbeets was also studied at the Panhandle Research and Extension Center for both sprinkler and furrow irrigation systems. In these experiments, irrigation was either limited or stopped starting in mid-August. The results are given in figures 3a and 3b and show a yield decline as water stress increased for sprinkler and furrow systems, respectively. The decline however, was not as great as what might be expected. If the sugarbeet is allowed to develop a extensive roots system and water is available in the soil profile, it is capable of retrieving water from depths greater than 3 to 4 ft. In a current experiment irrigation water is being withheld from sugarbeets from July 15 to August 15. Preliminary results indicate very little difference in yield between full irrigation and no irrigation during the treatment period. The results indicate that like wheat and sunflowers, sugarbeets can effectively extract water from depths much greater than 3.0 ft and perhaps sustain periods of water stress without adversely impacting yield.

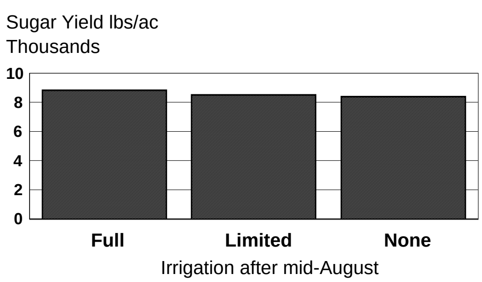

Figure 3a. Effect of late season water stress on sugarbeet yield using sprinkler irrigation.

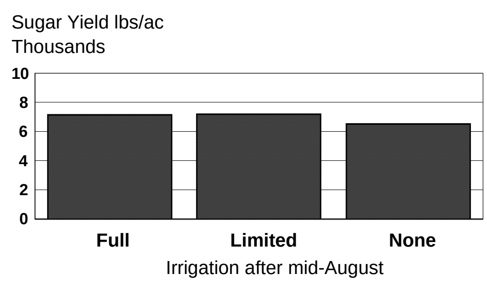

Figure 3. Effect of late season water stress on sugarbeet yield using furrow irrigation.

Based on the results of the dry bean and sugarbeet experiments, if water is limited and the irrigator has the ability to choose when water supplies can be used, the choice should be to use water early in the season. Reducing irrigation late in the season has a smaller impact on yield than reducing irrigation early in the season and risking more of a yield reduction.

RESPONSE OF IRRIGATED SUNFLOWERS TO WATER TIMING

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INTRODUCTION

With declining water supplies in the Central Great Plains Region, conservation of water is an important issue for producers. Many areas have reported declining groundwater levels for 20 or more years within Colorado, Kansas and Nebraska. As groundwater levels decline, well output has declined in some regions to the point that systems are limited in their capability to fully irrigate a single crop under the entire system. When producers are faced with this situation, they are faced with only being able to limit irrigate a single crop or they must irrigate two or more crops under a single system and properly time the water needs of each crop. Sunflowers are a crop that has been proven to be beneficial to dryland producers because of its drought tolerance. However, little is known about the responsiveness of sunflowers to limited water and the timing of water needs for that crop.

Methods and Materials

The experimental site was at the U.S. Central Great Plains Research Station at Akron, CO. Soil was a Weld silt loam (fine, smectitic, mesic, Aridic Argiustolls) with a plant available water holding capacity of 2 inches per foot. The previous crop was rainfed corn in 2003. The irrigated sunflowers were planted May 25, 2004 no-till into the corn stubble. The varieties planted were Triumph 658 Nu-Sun for oil and Triumph 765C for confectionary. Planting rates were 26,000 seeds per acre for oil and 24,000 for confectionary in 30 inch rows. Fertilizer application was 100 lbs/acre of nitrogen and 30 lbs/acre of phosphorous. Furadan was applied at 1 quart per acre in-furrow at planting for stem weevil control. Herbicide application was Spartan at 2 oz/acre, prowl at 2 pt/acre and Round-up at 20 oz/acre applied two weeks before planting and hand weeding for escape weeds.

A split-plot design was used for this experiment with timing of water application being the main plot with sunflower type (oil vs confection) as the sub-plot. Main plots were 15 ft (6 rows) by 130 feet with sub-plots 65 feet long. Water was applied with a surface drip system on 60 inch centers. The application rate of the system was 0.08 inches per hour and operated to apply 0.8 to 1.0 inches per application. Soil moisture was monitored weekly with the neutron attenuation method to a depth of 5 feet in 1 foot increments for each treatment. Plots were hand harvested on October 7, 2003. The middle two rows were harvested for a total row length of 20 feet.

RESULTS

Weather and Irrigation Amounts

Precipitation during the three year period ranged from excessively dry in 2002 to slightly above normal in 2003. Precipitation for the cropping year of 2004 was characterized by normal precipitation for the cropping season (Table 1). Precipitation for the cropping year was 84% of average. Precipitation from Oct 2003 to June 2004 was 63% of average. Precipitation during June 200 to September 2004 was 103% of average. Precipitation during 2002 was below normal during the entire growing season. Non-growing season precipitation was 33% of normal with growing season precipitation being 80% of normal. Precipitation during 2003 was typified by above normal precipitation during the non-growing season and below normal precipitation during the growing season.

Irrigation amounts for 2002 to 2004 are reported in Table 2. Total irrigation in 2004 was the greatest due to a 3 inch pre-irrigation to increase beginning soil moisture. Irrigation amounts in 2002 and 2003 were similar although total precipitation was less in 2002.

Grain Yield

Grain yields for confection and oil sunflowers are reported in Table 3 and 4. Grain yields for confection and oil generally increased as the amount of water applied increased. Maximum yields for confection sunflowers occurred with irrigation prior to the R5 growth stage. Yields for Full Water, R1-R5, and R4-R5 irrigation strategies were similar in 2003 and 2004. However, in 2002, lack of beginning soil moisture reduced yields for the R4-R5 irrigation strategy as compared to the full water or R1-R5 irrigation strategies. Withholding irrigation until after the R5 growth stage resulted in reduced grain yields as compared to irrigation early but was greater than dryland management.

During years with adequate soil moisture such as 2003, irrigating during any early reproductive growth stage had similar years with a tendency for irrigation during the R1-R5 growth stages being advantageous. During years with marginal soil moisture, irrigation during the vegetative growth stages increased yields slightly, but no significantly. However, during years with inadequate soil moisture such as 2002, irrigation during the vegetative or early reproductive growth stages increased yields.

Grain yields for full water oil sunflowers were greater than all other strategies two of three years. Only in 2003, when stored soil moisture was adequate, were grain yields for all irrigation strategies equal. Grain yields for the R1-R3 irrigation strategy were significantly lower than all other irrigation strategies in 2004. Irrigating during the early reproductive growth stages had a tendency to create unfavorable growing conditions for the plant later in the growing season that resulted in the lower yields. Irrigation management strategies of R1-R5 and R4-R5 had equal yields which were slightly greater than the R6-R7 growth stage. Withholding irrigation until the R6 growth stage was after the yield determination growth stage for irrigated oil sunflower.

Irrigation Water Use Efficiency

How efficient each irrigation strategy was is important in limited water management. Irrigation water use efficiency (IWUE) is defined as the following:

$$IWUE = \frac{\text{Irrigated Yield} - \text{Rainfed Yield}}{\text{Irrigation Amount}}$$

The IWUE shows how efficient irrigation water applied during each growth stage was converted to grain yield. A higher IWUE indicated each inch of irrigation applied was converted to more grain production.

Maximum IWUE for oil sunflowers occurred when the crop was irrigated during the R4-R5 growth stages (Table 5). Each inch of water applied at this growth stage was converted to approximately 244 lbs/acre-in of seed for 2002 to 2004. Only in 2002 did the R4-R5 growth stage not have the greatest IWUE. Irrigation during the R6-R7 growth stage had the next highest IWUE with Full Water management having the lowest IWUE for 2002 to 2004

Maximum IWUE for confection sunflowers occurred when the crop was irrigated during the R4-R5 growth stages (Table 6). Irrigation water use efficiencies for R1-R5 and R1-R3 strategies were similar with approximately 130 lbs/acre-in increase in yield. Full water and R6-R7 management strategies resulted in the lowest IWUE on average. Irrigation after the R6 growth stage was to late to significantly increase yields while irrigation during the vegetative growth stage was not as efficient as waiting until the reproductive growth stages.

The lower IWUE for full water management for both oil and confection sunflower would indicate that irrigation during the vegetative growth stages was not an efficient irrigation strategy for limited water supplies.

Seed Size

Irrigation timing significantly impacted seed size of confection sunflower (Table 7). Irrigation earlier in the growth stages resulted in greater large and jumbo seed size as compared to irrigating after the R5 growth stage. Seed size for the R6-R7 strategy was lower than the early strategies but similar to dryland each of the three years. Seed size for the R4-R5 strategy was similar to full water and R1-R5 strategies in 2003 and 2004 but significantly less in 2002. Stopping irrigation after the R3 growth stage resulted in lower seed size two of the three years. Only in 2003 when soil moisture was adequate did withholding irrigation after the R3 growth stage not reduce seed size.

Oil Content and Production

Oil content of sunflower was significantly affected by irrigation timing (table 7). Delaying irrigation until the R6 growth stage significantly increased oil content each of the three years as compared to the other irrigation strategies. Irrigating during the R4-R5 growth stages increased oil content two of three years. Only in 2004 was oil content of this irrigation strategy significantly lower than full water or dryland oils. Irrigation management strategies that applied water during the early reproductive growth stages generally had lower oil contents. However, ending irrigation at the R3 growth stage significantly reduced oil content as compared to full water management.

Oil contents were greatest in 2002 which was a hot and drier year as compared to 2003 and 2004. Oil contents in 2004 were the lowest in each of the three years with oil contents less than 40% for most strategies. Temperatures during 2004 were lower than average with low temperatures less than 40 degrees F several days.

Total production of oil per acre incorporates yield and oil content (table 8). Average production of oil per acre for 2002 to 2004 was greatest for full water management. If 2002 was not used for the average due to the excessive drought and lack of beginning soil moisture, oil production for full water and R4-R5 management strategies were similar. Although yields for the R6-R7 irrigation strategy were reduced as compared to the full water, R1-R5 and R4-R5 management strategies, oil production was reduced by approximately 150 lbs/acre. The R1-R3 irrigation management strategy produced the lowest amount of oil per acre of the irrigated strategies and oil slightly more than dryland production.

CONCLUSIONS

Total yields of oil and confection sunflower generally increased as irrigation applied increased. However, several water saving strategies have been identified. Irrigated during the early reproductive growth stage had similar yields and seed sized for confection sunflower as compared to full water management. However, irrigating during the R1-R5 growth stages reduced the amount of irrigation applied by approximately 3.6 inches as compared to full water management. Irrigating during the vegetative and late reproductive growth stages did not significantly increase yields or seed size components. However, irrigation must be continued through the R5 growth stages. Ending irrigation prior to that growth stage reduced grain yield and seed size.

Full water management for oil sunflowers produced the greatest yield and total lbs of oil per acre as compared to all other irrigation strategies. However, the irrigation strategy of R4-R5 produced only slightly less yield and lbs of oil per acre. The irrigation strategy of R4-R5 required approximately 6 inches less irrigation. If water is limited, this irrigation strategy may be economically viable due to the potential of increasing irrigated acres.

Table 1. Growing year precipitation from October to September 2002 to 2004.

	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug	Sep.
							Inches					
2001-02	0.63	0.78	0.00	0.09	0.06	0.08	0.50	0.55	1.71	0.10	3.44	1.50
2002-03	1.04	0.39	0.03	0.22	0.41	2.34	2.47	4.05	4.34	0.90	1.54	0.26
2003-04	0.00	0.12	0.20	0.32	0.39	0.69	1.37	1.89	2.50	1.74	2.85	1.67
Average	0.90	0.55	0.40	0.33	0.34	0.83	1.64	2.96	2.45	2.67	2.08	1.23

Table 2. Irrigation amount for irrigation strategies.

	Dryland	R6-R7	R4-R5	R1-R3	R1-R5	Full Water
Year			Inches of Water			
2002	0	2.6	3.7	4.5	6.4	9.0
2003	0	1.8	3.0	3.8	5.3	9.3
2004	3.0	7.0	6.7	6.0	9.3	13.5
Average	1.0	3.8	4.5	4.8	7.0	10.6

Table 3. Confection Sunflower grain yields (2002 to 2004).

	Average Grain Yields 2002 lbs/acre	2003 lbs/acre	2004 lbs/acre	2002-2004 Overall Avg Lbs/acre	2003-2004 Overall Avg Lbs/acre
Dryland	299d	2550ab	1193c	1347	1871
R6-R7	688c	2249b	1778b	1572	2014
R4-R5	883bc	2875ab	2063ab	1940	2469
R1-R3	1137ab	2847ab	1797b	1927	2322
R1-R5	1192a	3139a	2173ab	2168	2656
Full Water	1335a	2617ab	2463a	2138	2540

Table 4. Oil Sunflower grain yields (2002 to 2004).

	Average Grain Yields 2002 lbs/acre	2003 lbs/acre	2004 lbs/acre	2002-2004 Overall Avg Lbs/acre	2003-2004 Overall Avg Lbs/acre
Dryland	468d	2387b	967d	1274	1677
R6-R7	771cd	2540ab	1956bc	1756	2248
R4-R5	1022bc	3031a	2297bc	2117	2664
R1-R3	1327b	2530ab	1803c	1887	2166
R1-R5	1287b	2701ab	2411bc	2133	2556
Full Water	1981a	2728ab	3147a	2619	2938

Table 5. Irrigation Water Use Efficiency for oil sunflowers (2002 to 2004).

	Average Oil Yield 2002 lbs/acre-in	2003 lbs/acre-in	2004 lbs/acre-in	2002-2004 Overall Avg lbs/acre-in	2003-2004 Overall Avg lbs/acre-in
R6-R7	117	88	250	174	200
R4-R5	150	215	361	244	295
R1-R3	191	37	283	163	144
R1-R5	128	59	231	143	152
Full Water	168	37	207	140	127

Table 6. Irrigation Water Use Efficiency for confection sunflowers (2002 to 2004).

	Average Oil Yield 2002 lbs/acre-in	2003 lbs/acre-in	2004 lbs/acre-in	2002-2004 Overall Avg lbs/acre-in	2003-2004 Overall Avg lbs/acre-in
R6-R7	150	-172	148	81	50
R4-R5	158	108	236	171	179
R1-R3	186	78	204	154	133
R1-R5	140	111	157	137	135
Full Water	115	7	120	82	67

Table 7. Seed size and oil content for confection and oil sunflowers.

	Confection Seed Size						Oil Content		
	2002		2003		2004		2002	2003	2004
Irrigation	% Large	% Jumbo	% Large	% Jumbo	% Large	% Jumbo	%	%	%
Dryland	0.4d	0.0d	70.3b	30.9b	29.5c	3.6c	48.5ab	43.9b	36.8b
R6-R7	9.5d	0.2d	70.8b	31.8b	32.8bc	6.5c	49.7a	47.3a	41.4a
R4-R5	22.9c	0.5d	75.0ab	44.7ab	78.0a	35.9b	47.2b	47.7a	35.1c
R1-R3	55.0b	16.6c	80.9ab	43.5ab	45.5b	14.4c	43.3d	41.3c	34.5c
R1-R5	64.2ab	30.2b	82.1ab	49.6ab	85.7a	60.1a	45.2c	43.4bc	34.8c
Full Water	72.2a	48.5a	85.6a	61.8a	78.3a	50.7a	45.3c	42.5bc	37.9b

Table 8. Oil yield for oil sunflowers (2002 to 2004).

	Average Oil Yield			2002-2004	2003-2004
	2002	2003	2004	Overall Avg	Overall Avg
	Lbs oil/ac	Lbs oil/ac	Lbs oil/ac	Lbs oil/ac	Lbs oil/ac
Dryland	227	1047	356	543	702
R6-R7	383	1202	809	798	1006
R4-R5	483	1446	806	911	1126
R1-R3	574	1045	621	747	833
R1-R5	581	1171	839	864	1005
Full Water	897	1160	1193	1083	1176

SUMMER CROP PRODUCTION AS RELATED TO IRRIGATION CAPACITY

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INTRODUCTION

In arid regions, it has been a design philosophy that irrigation system capacity be sufficient to meet the peak evapotranspiration needs of the crop to be grown. This philosophy has been modified for areas having deep silt loam soils in the semi-arid US Central Great Plains to allow peak evapotranspiration needs to be met by a combination of irrigation, precipitation and stored soil water reserves. The major irrigated summer crops in the region are corn, grain sorghum, soybean and sunflower. Corn is very responsive to irrigation, both positively when sufficient and negatively when insufficient. The other crops are less responsive to irrigation and are sometimes grown on more marginal capacity irrigation systems. This paper will discuss the nature of crop evapotranspiration rates and the effect of irrigation system capacity on summer crop production. Additional information will be provided on the effect of irrigation application efficiency on irrigation savings and corn yields. Although the results presented here are based on simulated irrigation schedules for 33 years of weather data from Colby, Kansas (Thomas County in Northwest Kansas) for deep silt loam soils, the concepts have broader application to other areas in showing the importance of irrigation capacity for summer crop production.

SUMMER CROP EVAPOTRANSPIRATION RATES

Crop evapotranspiration (ET) rates vary throughout the summer reaching peak values during the months of July and August in the Central Great Plains. Long term (1972-2004) July and August corn ET rates at the KSU Northwest Research Extension Center, Colby, Kansas have been calculated with a modified Penman equation (Lamm, et. al., 1987) to be 0.267 and 0.249 inches/day, respectively (Figure 1). However, it is not uncommon to observe short-term peak corn ET values in the 0.35 – 0.40 inches/day range. Occasionally, calculated peak corn ET rates may approach 0.5 inches/day in the Central Great Plains, but it remains a point of discussion whether the corn actually uses that much water on those extreme days or whether corn growth processes essentially shut down further water losses. Individual years are different and daily rates vary widely from the long term average corn ET rates (Figure 1). Corn ET rates for July and August of 2004 were 0.245 and 0.229 inches/day, respectively, representing an approximately 8% reduction from the long-term average rates. In contrast, the corn ET rates for July and August of 2003 were 15% greater than the long term average rates. Irrigation systems must supplement precipitation and soil water reserves to attempt matching average corn ET rates and also provide some level of design flexibility to attempt covering year-to-year variations in corn ET rates and precipitation.

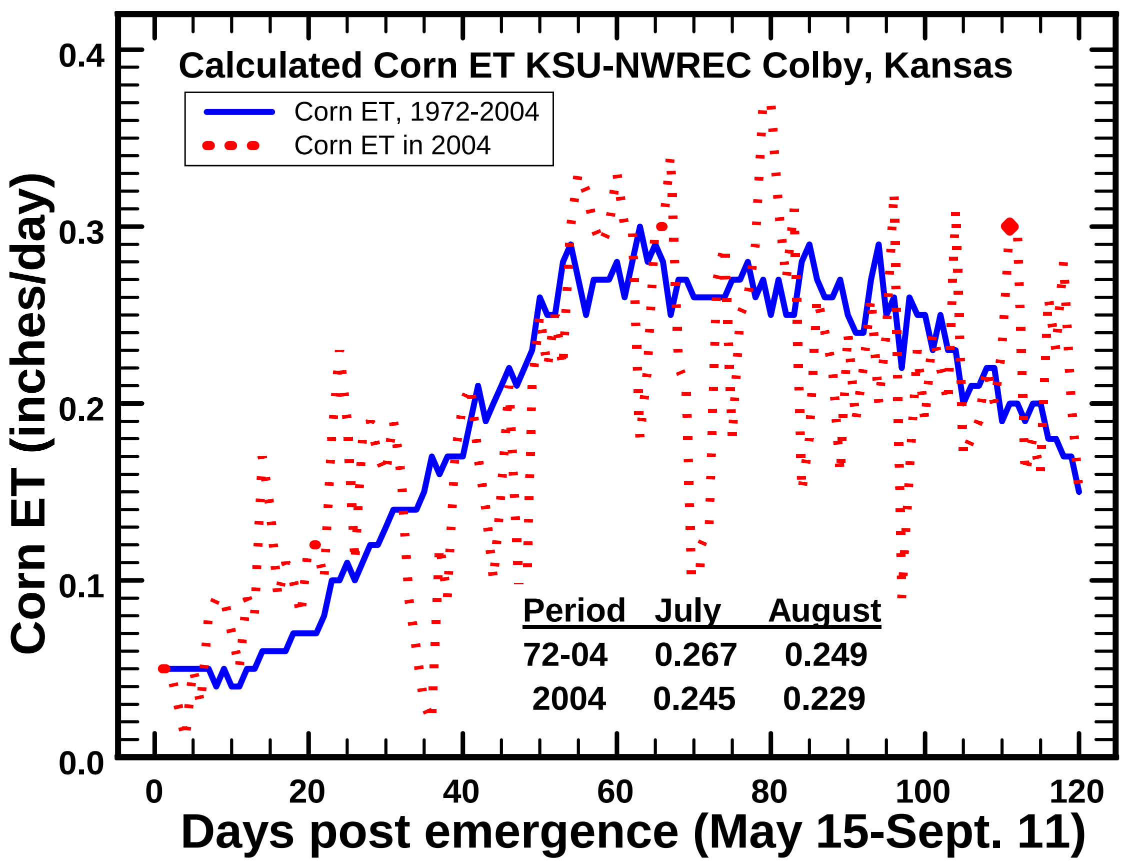

Figure 1. Long term corn evapotranspiration (ET) daily rates and ET rates for 2004 at the KSU Northwest Research-Extension Center, Colby Kansas. ET rates calculated using a modified Penman approach (Lamm et. al., 1987).

DESIGN IRRIGATION CAPACITIES

Simulation of irrigation schedules for Colby, Kansas

Irrigation schedules (water budgets) for the major summer crops were simulated for the 1972-2004 period using climatic data from the KSU Northwest Research-Extension Center in Colby, Kansas. Reference evapotranspiration was calculated with a modified Penman equation (Lamm, et. al., 1987) and further modified with empirical crop coefficients (Figure 2) for the location to give the crop ET. Typical emergence, physiological maturity, and irrigation season dates were used in the simulation (Table 1). The 5-ft. soil profile was assumed to be at 85% of field capacity at corn emergence (May 15) in each year. Effective rainfall was allowed to be 88% of each event up to a maximum effective rainfall of 2.25 inches/event. The application efficiency, Ea, was initially set to 100% to calculate the simulated full net irrigation requirement, SNIR. Center pivot sprinkler irrigation events were scheduled if the calculated irrigation deficit exceeded 1 inch.

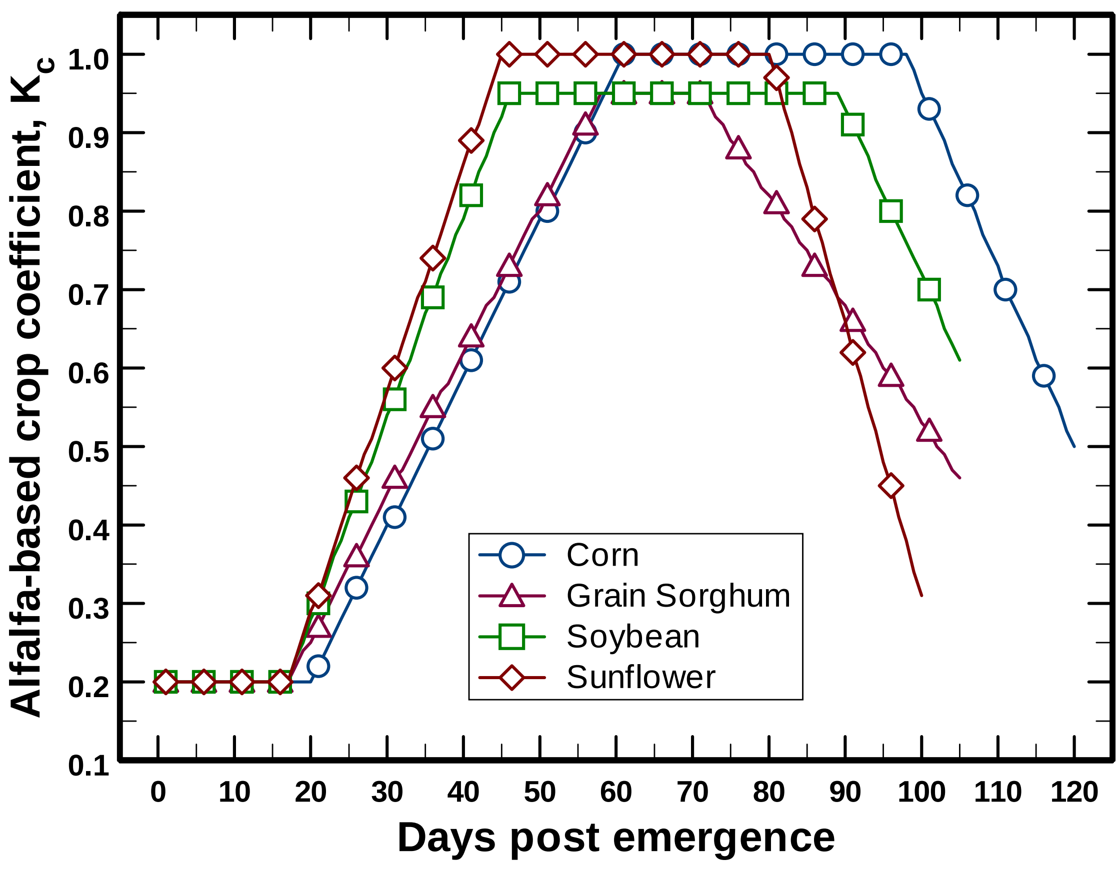

Figure 2. Alfalfa-based crop coefficients used in the simulated irrigation schedules and crop yield modeling.

Table 1. Parameters and factors used in the simulation of irrigation schedules and crop yield modeling.

Parameter	**Corn**	**Grain Sorghum**	**Soybean**	**Sunflower**
Emergence date	May 15	June 1	May 25	June 15
Physiological maturity date	September 11	September 13	September 16	September 11
Crop season, days	120	105	115	100
End of irrigation season	September 2	September 4	September 7	September 2
Irrigation season, days	110	95	105	90
Factors for crop yield model				
Vegetative period, days	66	54	38	53
Susceptibility factor (vegetative)	36.0	44.0	6.9	43.0
Flowering period, days	9	19	33	17
Susceptibility factor (flowering)	33.0	39.0	45.9	33.0
Seed formation period, days	27	22	44	23
Susceptibility factor (formation)	25.0	14.0	47.2	23.0
Ripening period, days	18	10	-	7
Susceptibility factor (ripening)	6.0	3.0	-	1.0
Slope on yield model	16.85	12.2	4.57	218.4
Intercept on yield model	-184	-84.7	-35.7	-1189

Using this procedure, the mean simulated net irrigation requirement (SNIR) for corn, grain sorghum, soybean and sunflower for the 33-year period was 14.85, 10.73, 14.52, and 12.24 inches respectively (Table 2.). The maximum SNIR for the crops was in 1976, ranging from 17 to 21 inches, while the minimum occurred in 1992, ranging from 3 to 5 inches. This emphasizes the tremendous year-to-year variance in irrigation requirements. Good irrigation management will require the irrigator to use effective and consistent irrigation scheduling.

July and August required the highest amounts of irrigation for all four summer crops with the two months averaging 84% of the total seasonal needs (Table 3). However, it might be more appropriate to look at the SNIR and seasonal distribution in relation to probability, similar to the probability tables from the USDA-NRCS irrigation guidebooks. In this sense, SNIR values will not be exceeded in 80 and 50% of the years, respectively (Table 4). The minimum gross irrigation capacities (62-day July-August period) generated using the SNIR values are 0.266, 0.188, 0.240, and 0.213 inches/day (50% exceedance levels) for corn, grain sorghum, soybean and sunflower, respectively, using center pivot sprinklers operating at 85% Ea (Table 4).

Table 2. Simulated net irrigation requirements for four major irrigated summer crops for Colby, Kansas, 1972-2004.

Year	Corn	Grain Sorghum	Soybean	Sunflower
1972	9	6	8	7
1973	15	11	15	12
1974	17	13	17	14
1975	13	10	14	12
1976	21	17	21	18
1977	10	7	10	8
1978	19	14	19	17
1979	8	5	8	8
1980	19	14	19	15
1981	15	11	14	11
1982	11	9	10	10
1983	21	16	21	19
1984	19	15	19	17
1985	16	10	14	10
1986	17	13	16	13
1987	16	12	16	14
1988	19	14	19	16
1989	14	10	14	11
1990	17	13	16	14
1991	16	12	16	14
1992	5	3	5	4
1993	8	5	8	5
1994	16	11	15	14
1995	16	12	16	15
1996	7	4	7	4
1997	13	8	12	9
1998	12	7	11	9
1999	10	7	11	9
2000	20	14	19	15
2001	20	15	19	16
2002	20	14	19	15
2003	18	13	18	16
2004	13	9	13	13
Maximum	21	17	21	19
Minimum	5	3	5	4
Mean	14.85	10.73	14.52	12.24
St. Dev.	4.41	3.68	4.35	3.99

Table 3. Average (33 year, 1972-2004) monthly distribution, %, of simulated net irrigation requirements for four major irrigated crops at Colby, Kansas.

Crop	June	July	August	September
Corn	13.71	42.29	42.38	1.62
Grain Sorghum	6.23	38.39	50.90	4.48
Soybean	10.08	42.90	40.87	6.15
Sunflower	2.37	25.16	53.71	18.77

Table 4. Simulated net irrigation requirements (SNIR) of 4 summer crops not exceeded in 80 and 50% of the 33 years 1972-2004, associated July through August distributions of SNIR, and minimum irrigation capacities to meet July through August irrigation needs, Colby, Kansas.

Criteria	***Corn***		***G. Sorghum***		***Soybean***		***Sunflower***	
	SNIR	***July-August***	***SNIR***	***July-August***	***SNIR***	***July-August***	***SNIR***	***July-August***
SNIR value not exceeded in 80% of the years	19 in.	93.8% 17.8 in	14 in.	100.0% 14.0 in.	19 in.	88.9% 16.9 in.	16 in.	84.2% 13.5 in.
July – August capacity requirement	0.287 in./day		0.226 in./day		0.272 in./day		0.217 in./day	
Minimum gross capacity at 85% application efficiency	0.338 in./day		0.266 in./day		0.320 in./day		0.256 in./day	
Minimum gross capacity at 95% application efficiency	0.302 in./day		0.238 in./day		0.287 in./day		0.229 in./day	
SNIR value not exceeded in 50% of the years	16 in.	87.5% 14.0 in.	11 in.	90.0% 9.9 in.	15 in.	84.2% 12.6 in.	14 in.	80.0% 11.2 in.
July – August capacity requirement	0.226 in./day		0.160 in./day		0.204 in./day		0.181 in./day	
Minimum gross capacity at 85% application efficiency	0.266 in./day		0.188 in./day		0.240 in./day		0.213 in./day	
Minimum gross capacity at 95% application efficiency	0.238 in./day		0.168 in./day		0.214 in./day		0.190 in./day	

It should be noted that this simulation procedure shifts nearly all of the soil water depletion to the end of the growing season after the irrigation season has ended and that it would not allow for the total capture of major rainfall amounts (greater than 1 inch) during the irrigation season. *Thus, this procedure is markedly different from the procedure used in the USDA-NRCS-Kansas guidelines (USDA-*

NRCS-KS, 2000, 2002). However, the additional inseason irrigation emphasis does follow the general philosophy expressed by Stone et. al., (1994), that concluded inseason irrigation is more efficient than offseason irrigation in corn production. It also follows the philosophy expressed by Lamm et. al., 1994, that irrigation scheduling with the purpose of planned seasonal soil water depletion is not justified from a water conservation standpoint, because of yield reductions occurring when soil water was significantly depleted. Nevertheless, it can be a legitimate point of discussion that the procedure used in these simulations would overestimate full net irrigation requirements because of not allowing large rainfall events to be potentially stored in the soil profile. In simulations where the irrigation capacity is restricted to levels significantly less than full irrigation, any problem in irrigating at a 1-inch deficit becomes moot, since the deficit often increases well above 1 inch as the season progresses.

There are many different equivalent ways of expressing irrigation capacity including depth/time, flowrate/system, flowrate/area, and time to apply given irrigation depth. Some of these equivalent irrigation capacities are shown in Table 5.

Table 5. Some common equivalent irrigation capacities.

Irrigation capacity, inches/day	*Irrigation capacity, gpm/125 acres*	*Irrigation capacity, gpm/acre*	*Irrigation capacity, days to apply 1 in.*
0.333	786	6.29	3
0.250	589	4.71	4
0.200	471	3.77	5
0.167	393	3.14	6
0.143	337	2.69	7
0.125	295	2.36	8
0.111	262	2.10	9
0.100	236	1.89	10

SIMULATION OF CROP YIELDS AS AFFECTED BY IRRIGATION CAPACITY

Model description

The irrigation scheduling model was coupled with a crop yield model to calculate crop grain yields as affected by irrigation capacity. In this case, the irrigation level is no longer full irrigation but was allowed to have various capacities (no irrigation and 1 inch every 3, 4, 5, 6, 8 or 10 days). Irrigation was scheduled according to climatic needs, but was limited to these capacities.

Crop yields for the various irrigation capacities were simulated for the same 33 year period (1972-2004) using the irrigation schedules and a yield production function developed by Stone et al. (1995). In its simplest form, the model results in the following equation,

Yield = Yldintercept + (YldSlope x ETc)

with yield expressed in bushels/acre, yield intercept and slope as shown in Table 1 and ETc in inches. As an example, the equation for corn would be,

Yield = -184 + (16.85 x ETc)

Further application of the model reflects crop susceptibility weighting factors for specific growth periods (Table 1). These additional weighting factors are incorporated into the simulation to better estimate the effects of irrigation timing for the various system capacities. The weighting factors and their application to the model are discussed in detail by Stone et al. (1995). Soybean weighting factors were developed by use of yield response factors of Doorenbos and Kassam (1979).

Yield results from simulation

Although crop grain and oilseed yields are generally linearly related with ETc from the point of the yield threshold up to the point of maximum yield, the relationship of crop yield to irrigation capacity is a polynomial. This difference is because ETc and precipitation vary between years and sometimes not all the given irrigation capacity is required to generate the crop yield. In essence, the asymptote of maximum yield in combination with varying ETc and precipitation cause the curvilinear relationship. When the results are simulated over a number of years the curve becomes quite smooth (Figure 3.). Using the yield model, the 33 years of irrigation schedules and assuming a 95% application efficiency (Ea), the average maximum yield is approximately 200 bu/a, 130 bu/a, 65 bu/a and 2800 lb/a for corn, grain sorghum, soybean and sunflower, respectively. Estimates of crop yields as affected by irrigation capacity at a 95% application efficiency can be calculated from the polynomial equations in Table 6.

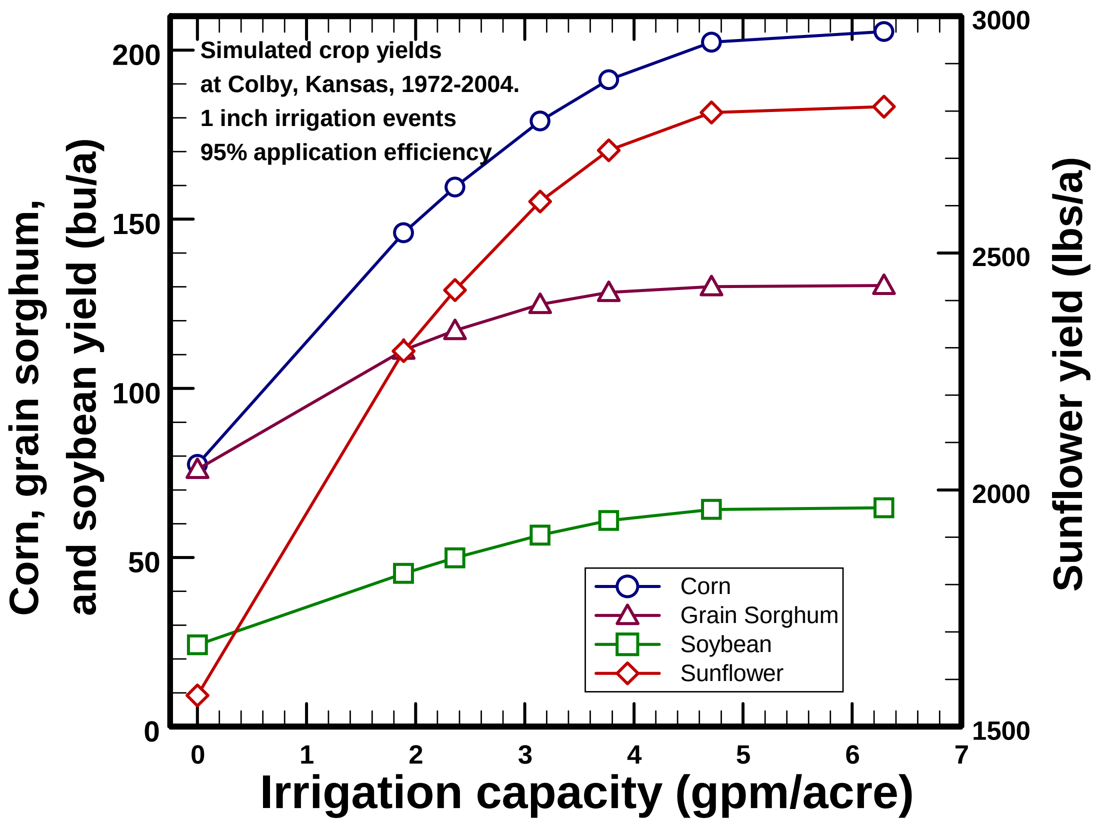

Figure 3. Simulated summer crop yields in relation to irrigation system capacity for the 33 years 1972-2004, Colby, Kansas.

Table 6. Relationship of crop yield to irrigation capacity for four summer crops at Colby, Kansas for 33 years (1972-2004) of simulation at a 95% application efficiency.

Crop	Crop yield relationship to irrigation capacity in gpm/a	R^2	Standard Error
Corn, bu/a	$Y = 77 + 42\ IC - 2.76\ IC^2 - 0.109\ IC^3$	0.9999	0.4
Grain Sorghum, bu/a	$Y = 76 + 25\ IC - 3.58\ IC^2 + 0.153\ IC^3$	0.9990	0.6
Soybean, bu/a	$Y = 24 + 12.4\ IC - 0.395\ IC^2 - 0.087\ IC^3$	0.9995	0.3
Sunflower, lb/a	$Y = 1565 + 474\ IC - 47.13\ IC^2 + 0.502\ IC^3$	0.9997	7.6

Crop yield penalty for insufficient irrigation capacity

The crop yield penalty for insufficient irrigation capacity at a 95% Ea can be calculated for various irrigation capacities by using the yield relationships in Table 6 and comparing these values to the maximum yield (Table 5). It can be seen that generally an irrigation capacity of 0.25 inches/day is sufficient for summer irrigated crop production. Lower capacities are possible for grain sorghum without much yield penalty.

Table 5. Penalty to crop yields for center pivot irrigated cron production at 95% application efficiency when irrigation capacity is below 0.33 inches/day (786 gpm/125 acres).   Results are from simulations of irrigation scheduling and yield for the 33 years 1972-2004, Colby, Kansas.

Equivalent irrigation capacities				***Penalties to crop yield***			
Inches /day	GPM /acre	Days to apply 1 inch	GPM/125 acres	Corn Yield, bu/a	G. Sorghum Yield, bu/a	Soybean Yield, bu/a	Sunflower yield, lb/a
0.333	6.29	3	786	0	0	0	0
0.250	4.71	4	589	3	0	0	2
0.200	3.77	5	471	15	2	4	98
0.167	3.14	6	393	27	6	8	202
0.125	2.36	8	295	46	13	15	380
0.100	1.89	10	236	59	18	19	512
No Irrigation				128	54	41	1242

Discussion of simulation models

The results of the simulations indicate yields decrease when irrigation capacity falls below 0.25 inches/day (589 gpm/125 acres). The argument is often heard that with today's high yielding corn hybrids it takes less water to produce corn. So, the argument continues, we can get by with less irrigation capacity. These two statements are misstatements. The actual water use (ETc) of a fully irrigated corn crop really has not changed appreciably in the last 100 years. Total ETc for corn is approximately 23 inches in this region. The correct statement is we can produce more corn grain for a given amount of water because yields have increased not because water demand is less. There is some evidence that modern corn hybrids can tolerate or better cope with water stress during pollination. However, once again this does not reduce total water needs. It just means more kernels are set on the ear, but they still need sufficient water to ensure grain fill. Insufficient capacities that may now with corn advancements allow adequate pollination still do not adequately supply the seasonal needs of the corn crop.

It should be noted that the yield model used in the simulations was published in 1995. The model may need updating to reflect yield advancements. However, it is likely that yield improvements would just shift the curves upward in Figure 3.

EFFECT OF APPLICATION EFFICIENCY ON IRRIGATION REQUIREMENTS AND CROP YIELDS

It has become popular in some water agencies to discount the potential of irrigation application efficiency improvements for saving water. The 33 years of simulated irrigation schedules were used to check the validity of this belief for corn using various irrigation capacities and application efficiencies. The results indicate that irrigation water savings will occur by improving application efficiency for capacities ranging from a very limited 1 inch every 10 days to full irrigation when averaged over the 33 year period (Table 6). Application efficiency improvements from 85 to 95% for a capacity of 1 inch every 3 days were 1.76 inches (11.4% savings) while the same improvements for a capacity of 1 inch every 8 days was only 0.12 inches (1.3% savings). The probability of needing to apply a given amount of irrigation or more for three selected capacities and application efficiencies is shown in Figure 4. In the case where the applied irrigation amount would only be exceeded in 25% of the years, the improvement in application efficiency from 85 to 95% would save 0.9, 0.32 and 0.11 inches (5.3, 2.5 or 1.1 %) for the irrigation capacities of 1 inch every 4, 6 or 8 days, respectively. Water savings were greatest for higher capacity systems when the irrigation requirements were greatest (hot and dry years). However, there is little or no opportunity to ultimately save irrigation water in extreme drought years such as 2000 through 2003 for marginal capacity systems. Any potential application efficiency improvements are readily used to help increase crop yields. The results suggest that it may be more important for water agencies to concentrate efforts at assuring that proper irrigation scheduling is utilized so that the potential irrigation system improvements can be fully realized.

The major advantage of irrigation system improvements that increase application efficiency is in the improvement in crop yields for lower capacity systems (Table 7). Corn yield increases of 15 to 20 bu/acre were obtained for lower capacity systems when the application efficiency was increased from 70 to 95%. The value of yield improvements due to higher application efficiency may well justify irrigation system improvements. This is probably one of the major reasons there has been a large conversion of furrow irrigation systems with lower application efficiency to center pivot sprinklers in the Great Plains region (Obrien et.al., 2000, 2001). Kansas Water Law requires that water diversion be used beneficially. The increased production from irrigation system improvements increases this benefit substantially for lower capacity systems. The U. S. and state economies benefit long term for these improvements and thus present federal and state cost-sharing programs for irrigation system improvements appear justified. In the cases where irrigation capacity is sufficient, there was little or no improvement in crop yields for higher application efficiency.

Table 6. Effect of improvements in application efficiency, E_a, on gross irrigation requirements (inches) for corn under various irrigation capacities at Colby, Kansas. Results are from simulated climatic-based irrigation schedules using 33 years (1972-2004) of weather data.

Statistic	**100% Ea**	**95% Ea**	**85% Ea**	**70% Ea**
	Full Irrigation, irrigate as needed.			
Maximum of 33 yr.	21.00	22.00	25.00	31.00
Minimum of 33 yr.	5.00	6.00	6.00	8.00
Mean of 33 yr.	14.85	15.79	17.76	21.91
	Limited to 1 inch/3 days, irrigate as needed			
Maximum of 33 yr.	21.00	22.00	25.00	30.00
Minimum of 33 yr.	5.00	6.00	6.00	8.00
Mean of 33 yr.	14.73	15.48	17.24	21.15
	Limited to 1 inch/4 days, irrigate as needed.			
Maximum of 33 yr.	20.00	20.00	21.00	22.00
Minimum of 33 yr.	5.00	6.00	6.00	8.00
Mean of 33 yr.	14.06	14.55	15.39	16.79
	Limited to 1 inch/5 days, irrigate as needed			
Maximum of 33 yr.	17.00	17.00	18.00	19.00
Minimum of 33 yr.	5.00	6.00	6.00	8.00
Mean of 33 yr.	12.61	12.88	13.42	14.24
	Limited to 1 inch/6 days, irrigate as needed			
Maximum of 33 yr.	15.00	15.00	16.00	17.00
Minimum of 33 yr.	5.00	6.00	6.00	7.00
Mean of 33 yr.	11.18	11.39	11.70	12.33
	Limited to 1 inch/8 days, irrigate as needed.			
Maximum of 33 yr.	12.00	12.00	13.00	13.00
Minimum of 33 yr.	4.00	5.00	6.00	6.00
Mean of 33 yr.	8.91	9.09	9.21	9.61
	Limited to 1 inch/10 days, irrigate as needed.			
Maximum of 33 yr.	10.00	10.00	10.00	11.00
Minimum of 33 yr.	4.00	4.00	4.00	5.00
Mean of 33 yr.	7.45	7.55	7.61	8.06

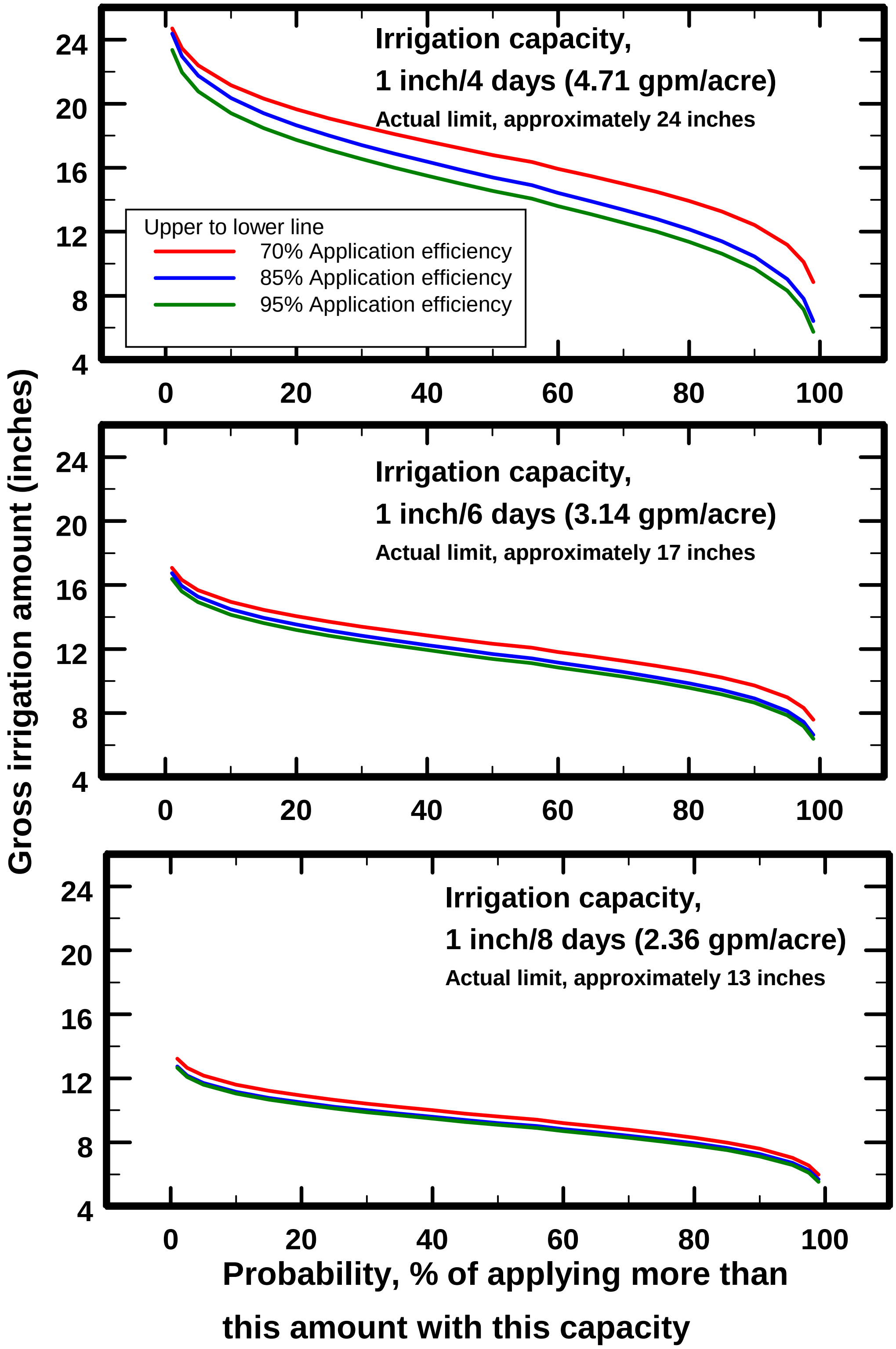

Figure 4. Gross irrigation amounts for corn as related to the probability of needing to apply that amount or more for three selected capacities and three selected application efficiencies assuming a normal distribution. Results from 33 years (1972-2004) of simulated irrigation schedules at Colby, Kansas.

Table 7. Effect of improvements in application efficiency, E_a, on corn grain yields (bu/acre) under various irrigation capacities at Colby, Kansas. Results are from simulated climatic-based irrigation schedules using 33 years (1972-2004) of weather data.

Statistic	**100% Ea**	**95% Ea**	**85% Ea**	**70% Ea**
	Full Irrigation, irrigate as needed.			
Maximum of 33 yr.	273	273	273	273
Minimum of 33 yr.	112	112	112	112
Mean of 33 yr.	205	205	205	205
	Limited to 1 inch/3 days, irrigate as needed			
Maximum of 33 yr.	273	273	273	273
Minimum of 33 yr.	112	112	112	112
Mean of 33 yr.	205	205	205	205
	Limited to 1 inch/4 days, irrigate as needed.			
Maximum of 33 yr.	266	261	258	236
Minimum of 33 yr.	112	112	112	112
Mean of 33 yr.	204	202	198	186
	Limited to 1 inch/5 days, irrigate as needed			
Maximum of 33 yr.	252	245	228	205
Minimum of 33 yr.	112	112	112	110
Mean of 33 yr.	194	191	184	171
	Limited to 1 inch/6 days, irrigate as needed			
Maximum of 33 yr.	225	217	208	198
Minimum of 33 yr.	112	112	109	102
Mean of 33 yr.	182	179	172	159
	Limited to 1 inch/8 days, irrigate as needed.			
Maximum of 33 yr.	200	198	192	188
Minimum of 33 yr.	105	103	98	91
Mean of 33 yr.	163	160	152	141
	Limited to 1 inch/10 days, irrigate as needed.			
Maximum of 33 yr.	190	188	184	178
Minimum of 33 yr.	96	94	90	82
Mean of 33 yr.	149	146	140	130

RECENT IRRIGATION CAPACITY STUDIES AT KSU-NWREC

Two different irrigation capacity studies for corn production were conducted at the KSU Northwest Research-Extension Center at Colby, Kansas during the period 1996-2001. One study was an examination of center pivot sprinkler irrigation performance for widely-spaced (10 ft) incanopy sprinklers at heights of 2, 4 and 7 ft. It should be noted that research has indicated the 10-ft. nozzle spacing is too wide for corn production (Yonts, et. al., 2005). Discussion of the center pivot sprinkler irrigation study (CP) will be limited to the 2-ft. height. The second study was with subsurface drip irrigation (SDI) evaluating the effect of plant population at various irrigation capacities. Only the data from the highest plant population (range of 30,000-35,000 over the 6 years) will be discussed here.

The weather conditions over the 6 year period varied widely. The years 1996-1999 can be characterized as wet years and the years 2000-2001 can be characterized as extremely dry years. Corn yield response to irrigation capacity varied greatly between the wet years and the dry years (Figure 5.) In wet years, there was better opportunity for good corn yields at lower irrigation capacities, but in dry years it was important to have irrigation capacities at 0.25 inches/day or greater.

Maximum corn yields from both these studies were indeed higher than those obtained in the modeling exercises in the previous section. This may lend more credibility to the discussion that the yield model needs to be updated to reflect recent yield advancement. However, the yields are plateauing at the same general level of irrigation capacity, approximately 0.25 inches/day.

It should be noted that it is not scientifically valid or recommended that direct comparisons of the two irrigation system types be made based on Figure 5. The studies had different objectives and constraints.

OPPORTUNITIES TO INCREASE DEFICIENT IRRIGATION CAPACITIES

There are many center pivot sprinkler systems in the region that this paper would suggest have deficient irrigation capacities. There are some practical ways irrigators might use to effectively increase irrigation capacities for crop production:

- Plant a portion of the field to a winter irrigated crop.
- Remove end guns or extra overhangs to reduce system irrigated area
- Clean well to see if irrigation capacity has declined due to encrustation
- Determine if pump in well is really appropriate for the center pivot design
- Replace, rework or repair worn pump

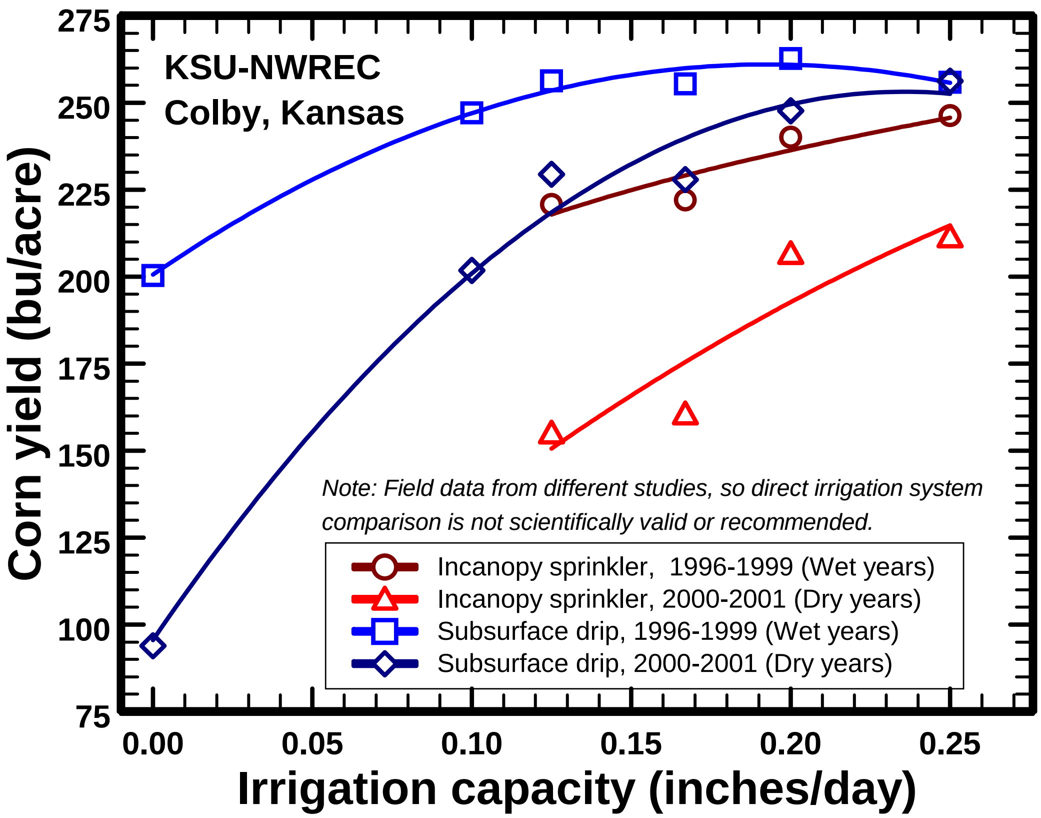

Figure 5. Corn grain yield as affected by irrigation capacity in wet years (1996-1999) and dry years (2000-2001) at the KSU Northwest Research-Extension Center, Colby, Kansas.

CONCLUDING STATEMENTS

The question often arises, *"What is the minimum irrigation capacity for an irrigated crop?"* This is a very difficult question to answer because it greatly depends on the weather, your yield goal and the economic conditions necessary for profitability. These crops can be grown at very low irrigation capacities and these crops are grown on dryland in this region, but often the grain yields and economics suffer. Considerable evidence is presented in this paper that would suggest that it may be wise to design and operate center pivot sprinkler irrigation systems in the region with irrigation capacities in the range of 0.25 inches/day (589 gpm/125 acres). In wetter years, lower irrigation capacities can perform adequately, but not so in drier years. It should be noted that the entire analysis in this paper is based on irrigation systems running 7 days a week, 24 hours a day during the typical 90 day irrigation season if the irrigation schedule (water budget) demands it. So, it should be recognized that system maintenance and unexpected repairs will reduce these irrigation capacities further.

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It is also available at http://www.oznet.ksu.edu/irrigate/OOW/P05/Lamm.pdf

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DETERMINING CROP MIXES FOR LIMITED IRRIGATION

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INTRODUCTION

Full irrigation is the amount needed to achieve maximum yield. However, when water supplies for irrigation are insufficient to meet the full evapotranspiration (ET) demand of a crop, limited irrigation management strategies will need to be implemented. The goal of these strategies is to manage the limited water to achieve the highest possible economic return. Restrictions on water supply are the primary reasons for using limited irrigation management. These restrictions may come in the form of mandated water allocations, from both ground water and surface water supplies, low yielding wells, and/or drought conditions which decrease available surface water supplies.

KEY MANAGEMENT STRATEGIES FOR DEALING WITH LIMITED IRRIGATION

The key management choices for dealing with insufficient irrigation supplies are as follows:

Cropping Management/Choices

- Reduce irrigated acreage and maintain the irrigation water applied
- Reduce amount of irrigation water applied to the whole field
- Rotate high water-requirement crops with those needing less water

Irrigation Management

- Delay irrigation until critical water requirement stages of the crop
- Manage the soil water reservoir to capture precipitation

Reducing irrigated acreage is one response to limited water supplies. When the irrigated area is reduced the amount of irrigation per acre more closely matches full irrigation requirements and it's corresponding per acre yield. Ideally, the land that reverts to dryland production should still produce some level of profitable returns. Another strategy may be to reduce the amount of irrigation per acre that is applied to the entire field. This would create the possibility for near normal crop yields if above normal precipitation occurred. In normal to below normal rainfall years, grain yields per acre would be less than those achieved with full irrigation. Rotating high water-requirement crops, such as corn, with crops needing less water would also be a possibility. Soybean, edible bean, winter wheat, and sunflower are the major crops with lower water requirements. Splitting fields between corn and one of these crops would reduce total water requirements for the field and distribute the water requirements across a longer portion of the growing season. For example, peak water demands for wheat are during May and June, while corn uses the most water during July and soybean water needs peak in August. Splitting the field into multiple crops allows producers with low-capacity wells to more completely meet the peak requirements of all crops.

Delaying irrigation until critical times is also a possible alternative if the volume of water is limited but well capacity is normal. Water availability during reproductive and grain filling growth stages is the most important for grain production. During vegetative growth some water stress can be tolerated without affecting grain yield and root development can be encouraged so that the crop can utilize deeper soil water. This period also typically coincides with the highest monthly rainfall amounts in the central plains. Field research from the West Central Research and Extension Center (WCREC) near North Platte has shown that corn can utilize water from deep in the soil profile when necessary. However, the irrigation system must be capable of keeping up with water demands during the reproductive growth stage of the crop if irrigation is delayed. Delayed irrigation is more feasible with center pivots than with furrow irrigation. In furrow irrigation, dry and cracked furrows do not convey water very well, especially during the first irrigation. A combination of furrow packing during the ridging operation, surge irrigation, and increased stream size may overcome some of the effects of late initiation of furrow irrigation.

An important management strategy under all limited irrigation situations is to capture and retain as much precipitation as possible. Crop residues on the soil surface intercept rainfall and snow, enhance infiltration, and reduce soil evaporation. Again, residue management is much easier with center pivot irrigation than furrow irrigation. Advancing water down a furrow may be more difficult with high residue levels. Ridge-till management along with furrow packing and surge irrigation may overcome some of these problems. Leaving room in the soil to store precipitation during the non-growing season enhances the possibility for capturing rainfall for the next growing season. Leaving room in the soil to store rainfall during the growing season may ensure more water availability during grain filling under limited water conditions.

It is very important to know the soil water status during the entire season. Limited irrigation management causes the irrigator to operate with more risk of crop water stress and grain yield reductions. Knowledge of soil water can help anticipate how severe the stress might be and help avoid disaster.

HOW CROPS RESPOND TO WATER

Yield vs Evapotranspiration

Crops respond to evapotranspiration (ET) in a linear relationship (Figure 1). For each inch of water that crop consumptively uses, a specific number of bushels is the resulting output. This relationship holds true unless excessive crop water stress occurs during the early reproductive growth stages. Where the response function intercepts the X-axis is the development and maintenance amount for each crop. The more drought tolerant crops (winter wheat) typically have lower development requirements than do high response crops (corn). Not all of the water that is applied to a crop through rainfall or irrigation is used by the crop. Losses such as runoff or leaching occur and are not useable for ET.

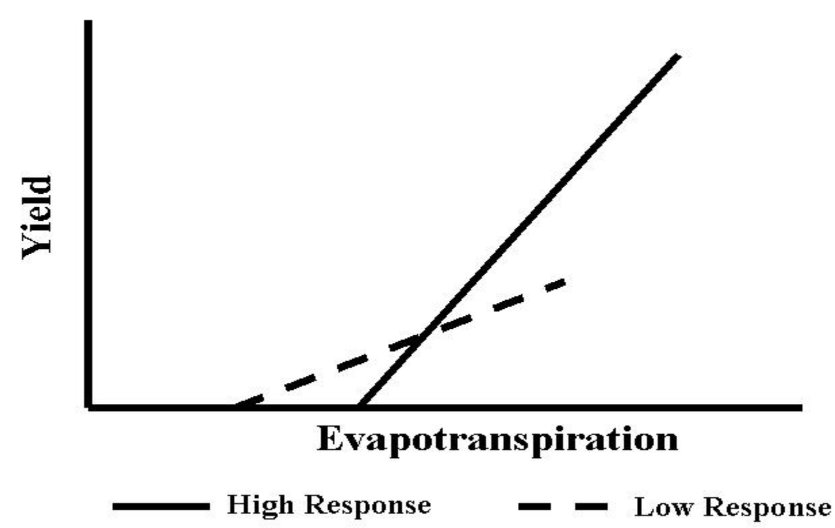

Figure 1. Generalized Yield vs Evapotranspiration response for high response crop and low response crop.

Yield vs Irrigation

Irrigation is applied to supplement rainfall when periods of ET are greater than available moisture. However, not all of the water applied by irrigation can be used for ET. Inefficiencies in applications by the system result in losses. As ET is maximized, more losses occur since the soil is nearer to field capacity and more prone to losses such as deep percolation (Figure 2). When producers are limited on the amount of water that they can apply by either allocations or low capacity wells, wise use of water is important for maximizing the return from water.

The yield increase of crops to water decreases as input levels approach maximum yield levels. In simple terms, as the amount of input and yield increases, the return from each unit is less than the previous unit. The yield increase from adding water from amount A to amount B is more than when increasing from amount B to C (figure 2). A producer must use this type of input to make informed decisions. The decision that must be made is irrigating at amount C with fewer acres or at amount B with more acres. The same question must be asked when comparing irrigation amount B to A. Developing a realistic yield vs irrigation production function is critical to managing limited water supplies. Producers must know what the yield increase from adding additional units of irrigation water to that crop is to determine the optimal amount of water to apply to that crop. The trade off that must be evaluated is the potential return per acre with each scenario.

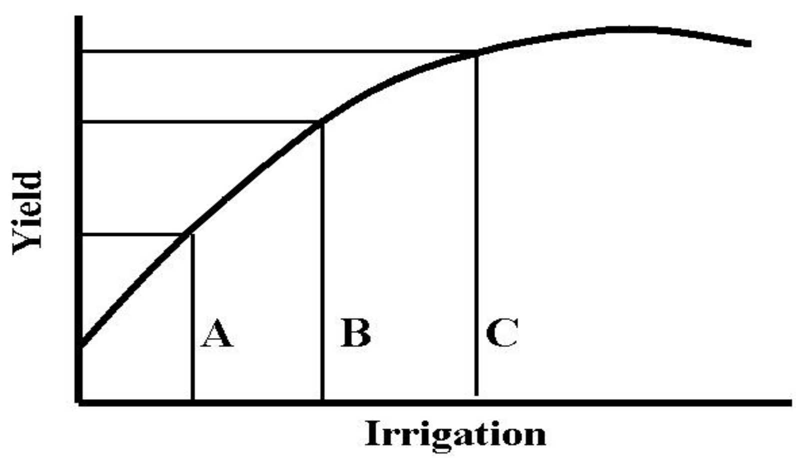

Figure 2. General Yield vs Irrigation Response.

ALLOCATING LIMITED WATER SUPPLIES

When water is unlimited, the management strategy is to add inputs such as water until the return from that input is equal in value to the added crop production. However, when water is limited, the management strategy should look at maximum return from each unit of input of water. When producers are limited in the amount of water they can either pump or are allocated and that amount of water is less than what is needed for maximum economic production, producers must look at management options that will provide the greatest possible returns to the operation.

A Single Irrigated Crop and a Dryland Crop

The easiest production option would be to look at a single irrigated crop with the remainder of production in either a dryland crop or fallow. When the amount of water is less than adequate for maximum production, producers must ask themselves whether the yield increase from increasing the amount of irrigation to each acre will offset the reduction in irrigated acres and increased dryland production. Increasing the amount of irrigation to a crop reduces the total number of irrigated acres. An example of this would be if you have 10 inches per acre available for irrigation. One option is to irrigate all acres at 10 inches. A second option would be to irrigate 2/3 of the acres at 15 inches and have the remainder at dryland production. The question to answer is "Does the yield increase offset the reduction in irrigated acres and having 1/3 of the potential irrigated acres in dryland production?" With a 130 acre irrigation system, a change in strategy such as this would reduce the irrigated acres from 130 to 87 acres and increase the dryland acres from 0 to 43 acres. If corn is the primary irrigated crop, several crops could be used as dryland crops in this scenario including winter wheat, soybeans or sunflowers.

Two or More Irrigated Crops

The use of two or more irrigated crops in a rotation may increase the number of irrigated acres as compared to a single irrigated crop and a dryland crop. The philosophy of this strategy is to use a high water use and response crop such as corn and a low water use and response crop such as winter wheat, soybean, dry edible beans or sunflowers. This strategy uses the yield vs irrigation to its maximum advantage. The first amounts of irrigation that are applied are used efficiently resulting in a yield response similar to that of the yield vs ET response shown in Figure 2.

The strategy to find the most economical split of water and acres is similar to that of the one irrigated crop strategy. Producers must look at the yield increase of adding water to one crop and the effect upon the irrigated acres and yield of the other irrigated crop. The potential options become more numerous because now producers need to look at increasing the irrigation amount for one crop versus reducing the irrigation amount to the other crop or increasing the number of irrigated acres for the other crop to compensate for the additional water to that crop. An example of this would be if you again had a water supply of 10 inches per acre available and are irrigating two crops such as corn and winter wheat. If a producer were irrigating corn at 15 inches per acre and wheat at 5 inches per acre, the irrigated acres would be even at 65 acres per crop to match your water supply. If this producer decides to irrigate wheat at 6 inches per acre, a first option would be irrigating corn at 14 inches per acre to keep the irrigated acres of each crop similar. A second option to keep corn at the 15 inch per acre of applied water would be to reduce the irrigated acres of corn and increase the irrigated acres of wheat. Using the second option, the final acres would be irrigating 58 acres of corn and 72 acres of wheat. When using three potentially irrigated crops, the options become even more numerous.

Rotation Considerations

It is important to look at the short-term rotation aspects with multiple crops being grown. One of the more important aspects is can a crop be grown after itself. There are several crops that do not perform well when planted after the same crop. The typical problem associated with this is the build up of diseases and weeds in the system. Crops such as winter wheat, soybeans or sunflowers should not be grown immediately after itself so this must be a consideration in how many acres of each crop can be grown or whether to grow more than two irrigated crops to increase the options in the rotation.

Low Capacity Systems

When working with low capacity systems, irrigation management strategies are limited due to the systems ability to meet the ET of the crop during the critical and high ET time periods. Irrigators must start their systems before the soil moisture reaches typical management criteria with best management practices. This must be done since the system can not replace the used soil moisture and crop ET so the soil must be managed so that it is closer to field capacity in anticipation of the greater crop ET demand later in the season. The use of more than one irrigated crop decreases the amount of irrigated acres at any one point in time so the system can apply water closer to or in excess of the demand by the crop.

Another important consideration with more than one irrigated crop is to choose crops that do not have critical water timing needs. Crops such as winter wheat and corn fit together well in a system such as this since wheat uses water in May and early June while corn requires water during July and early August. Planting two crops that have similar water timing needs together is not advantageous since both crops would be irrigated at the same time.

CALCULATING CROP ENTERPRISE COST OF PRODUCTION

Calculating cost of production and enterprise net returns is accomplished with enterprise budgeting techniques. In basic terms, an enterprise budget is a listing of income generated and expenses incurred to produce that income. In this setting, the enterprise is the production of corn, winter wheat, soybean, dry edible bean or sunflower, whichever crop is used in the rotation.

Enterprise Income

The income section of the budget lists all the income generated per acre from production of the crop. This would also include any secondary income such as aftermath grazing or roughage sales. For planning purposes, it would be more efficient not to include government programs in this analysis, but recognize net income will be lower as a result. The price received for each commodity can be based on national crop loan rates as a minimum. A realistic expectation of price received will produce realistic results in the analysis.

Enterprise Expenses

The expense section of the enterprise budget lists all the expenses associated with production of the commodity. The expenses can be broken down by variable and fixed costs. Variable costs of production are those costs that change with the level of production. For instance, fertilizer cost increase as more fertilizer is applied to increase crop yield. Other variable costs include seed, chemical inputs, fuel and labor among others. In the absence of accurate machinery operating costs, custom rate estimates can be substituted in the enterprise budget. A breakdown of all expenses included in the custom rate will be required to avoid double counting of fixed or variable expenses.

Fixed costs of production are those costs that need to be covered regardless of whether production occurs or not. These include machinery replacement, land and machinery debt payments, lease payments and other overhead costs such as insurance, taxes and interest payments.

Enterprise Net Income

The net income section of the budget calculates the difference between estimated cost and returns. A positive difference (income – expenses = net income) indicates there is a positive return to the factors of production whereas a negative return would indicate the income generated is not sufficient to cover the factors of production.

Once net return per acre is calculated for each enterprise, then net return for the chosen mix of crops to be produced under a limited irrigation situation can be determined. Working through this process on paper will identify the best option for producing the greatest net returns given resource limitations.

SPREADSHEET

A spreadsheet is under development to help producers determine the optimum crop mix is under development. This tool will allow producers to input cost of production, yield vs irrigation production functions and water allotments. The spreadsheet will then give producers a starting point in helping them determine the optimum crop mix and water allocation for several management options. This spreadsheet should be available in March or April.

CONCLUSION

It is important for producers to consider management and cropping practice changes when faced with limited water availability. Management strategies for limited water generally favor introduction of low water use crops to supplement high response crops. Full irrigation management strategies favor high water use-high response crops. An economic analysis will help producers with decisions on what irrigated crops are to be grown and how much water will be applied to each crop. It is important to for producers to have accurate information relating to yield response of crops to irrigation in making these decisions.

IRRIGATION MANAGEMENT STRATEGIES FOR CORN TO CONSERVE WATER

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INTRODUCTION

In the past, water has been plentiful and relatively inexpensive in most of Nebraska. Irrigation systems and irrigation scheduling equipment/procedures have made it challenging to put on just the right amount of water. Thus, many fields have been managed with the strategy that we will just put on a little extra water to make sure we have enough. In some fields, this has been a lot of extra water.

Today, water supplies are stretched very thin and pumping costs are much higher. In addition, more fields just simply do not have enough water to fully irrigate the crop. With this in mind, water conserving strategies are needed.

Research on conserving irrigation water in west central Nebraska has been underway since the 1920's. This research along with other work from around the world has led to the development of two water conserving strategies--Water Miser BMP and Deficit. Both conserve water by limiting irrigation water applied during the vegetative growth stage and relying upon precipitation and stored soil moisture. These two strategies can lower evapotranspiration (ET), which can potentially lower yields. In addition, the Deficit strategy lowers ET during the reproductive stages to keep water use down to the quantity available, which will defiantly lower yields. This strategy would only be used if water supplies were inadequate.

An irrigation management strategy, for purposes of this paper, is the plan or philosophy of how to decide the timing and amount of water to apply to the crop and should be developed before the crop is planted. Irrigation scheduling, on the other hand, is the in-season procedure used to carry out the management strategy.

The focus of this paper is on describing three irrigation management strategies for west central Nebraska. They are the traditional fully watered strategy and two that conserve water. Other water conserving practices that are not discussed here should be considered for irrigated corn production. Some practices to investigate include: good weed control, grow crops that need less water, and no-till or other tillage practices that minimize soil drying and leave the residue on the surface.

SOIL WATER TERMS

Before looking at the strategy in more detail, let's first review a few terms relating to soil water.

Soil holds water somewhat like a sponge. If one places the sponge in a container of water to completely fill the pore spaces with water and push out the air, the sponge would be saturated. This condition in the soil would also be called **saturation**.

The second term is **field capacity**. It describes the soil water content after the soil has been saturated and allowed to drain for about two days. This would be like lifting the sponge out of the container of water and allowing the free water to drain, but of course still leaving a lot of water in the sponge.

The third term is **permanent wilting point** and describes a soil water content that is so low that a plant growing in the soil would not be able to survive. This would be like wringing out all of the water we could get from our sponge. The soil, just like this wrung out sponge, still has some water left in it. This water is referred to as **unavailable water** and can only be completely removed by air-drying in an oven or in the sun.

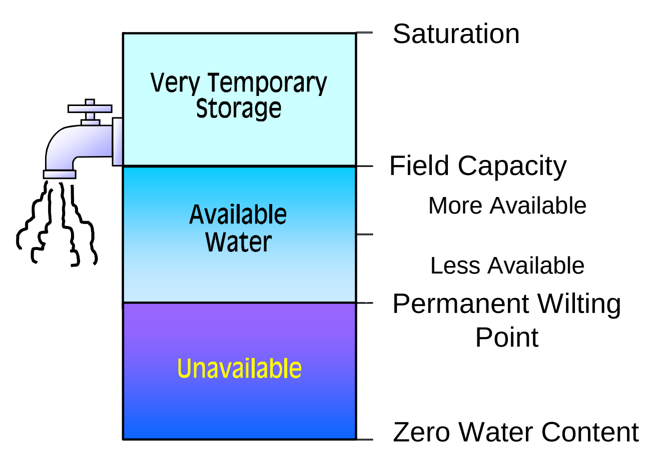

Figure 1. Relationship between different soil water terms. (Watts et al., 1998)

The water that is in the soil

between field capacity and permanent wilting point is called **plant available water**. Typical soils can hold between 1(fine sands)-2.5 (loam) inches of plant available water per foot of soil. The quantity of water in the soil that is above field capacity can be used by the crop, but remember this water will drain through the soil in a couple of days. Figure 1 shows the relationship between these terms.

The crop root depth is another important concept to understand that relates to the amount of water in the soil that the crop has access to. At emergence, a corn crop can access water in about the top 6 inches of soil and the roots can grow to a depth of more than 6 feet by the beginning dent growth stage if soil and moisture conditions encourage deeper root growth. Well-watered corn may only root to a depth of three feet. For irrigation scheduling purposes, corn is assumed to have access to the water in the top 6 inches at emergence, three feet by silking and 4 feet by beginning dent. A graphic depiction of these changes over the season is shown in Figure 2. An example, also shown in Figure 2., of this would be if we had corn at the silking stage (three foot root zone) growing in a soil that is at field capacity and holds 2 inches of plant available water per foot. The plant available water in the root zone would be 6 inches.

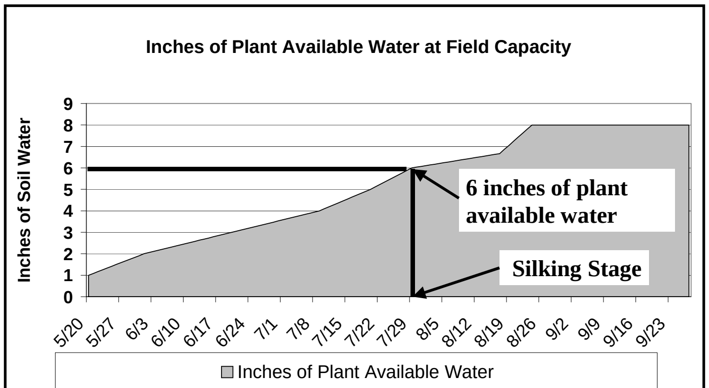

Figure 2. The gray shaded area shows the plant available soils water holding capacity in the root zone for a soil that holds 2 inches per foot of soil and how it changes during a typical growing season in Nebraska.

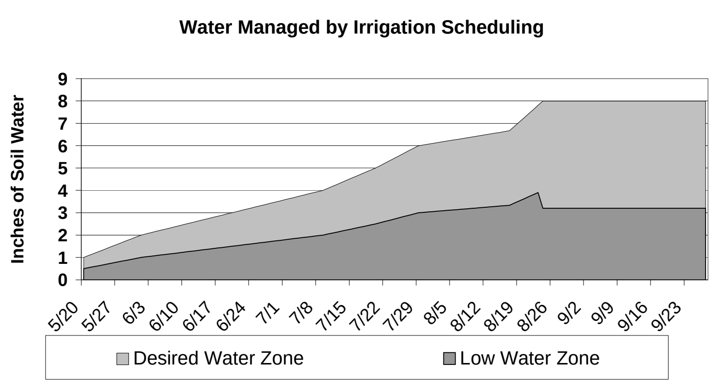

Figure 3. The gray shaded area shows the difference between the soils water holding capacity in the root zone and the maximum allowed soil moisture deficit.

FULLY WATERED

The Fully Watered management strategy is the traditional Best Management Practice (BMP) that has been around since the 1960's. It focuses on preventing moisture stress to the crop from planting to maturity by maintaining the plant available soil-water (in the active root zone) between field capacity and 50% depletion. Usually the soil in the root zone is kept one-half to one inch below field capacity to allow for rain storage. After the dough

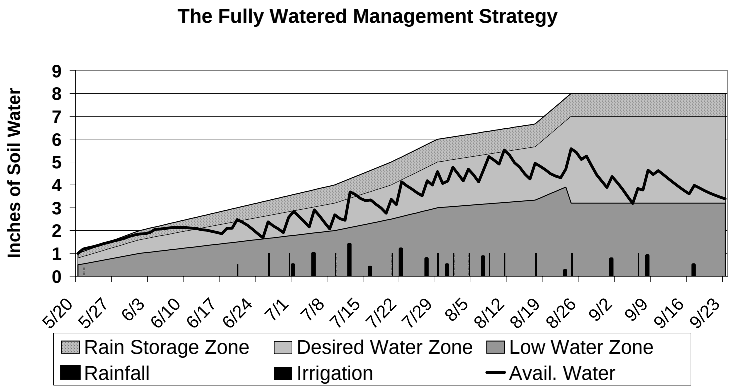

Figure 4. The gray shaded area shows desired water zone for the Fully Watered strategy. The black line showing available water should stay in the gray shaded area to indicate planned moisture level for the crop. Rain may push the line into the rain storage zone.

stage, the soil is allowed to dry down to 60% depletion.

The strategy can be illustrated by taking the top 50 percent of the plant available water as shown in Figure 3. This zone can be called the desired water zone. The way to tell if the Fully Watered strategy was met is to plot the actual plant available water in the root zone each day as shown in Figure 4. If the black line stays within the desired water zone on the chart, the management objective was met. The vertical lines indicate rain and irrigation applications.

MANAGEMENT TIPS

The fully watered strategy is the easiest of the three strategies to manage. Management needs to focus on: 1. when to start irrigation for the season, 2. limiting irrigation to keeping the soil moisture below field capacity to prevent water from draining below the root zone and to provide space to store in-season rain, and 3. when to stop irrigating at the end of the season, so the crop can use enough water to dry the field down to the 60% depletion level before it matures.

WATER MISER BMP

The Water Miser BMP irrigation management strategy focuses on saving water during the less sensitive vegetative growth stages and fully watering during the critical reproductive growth stages. Irrigation is delayed until about two weeks before tassel emergence of the corn, unless soil-water depletion exceeds 70% (in the active root zone). Once the crop reaches the reproductive growth stage, the plant available soil-water is maintained in a range between field capacity and 50% depletion. Usually the soil in the root zone is kept one-half to one inch below field capacity to allow for rain storage. After the hard dough stage, the soil is allowed to dry down to 60% depletion.

The principle behind this strategy has been shown in several research studies over the years. In the 1970's, at the former University of Nebraska's Sandhills Lab, Gilley et al.(1980) used a line-source sprinkler irrigation system to study the effects of water-stress on corn at the vegetative, pollination and grain filling stages. They found no significant yield reduction when the crop was moderately stressed during the vegetative stage. However, significant yield reductions were found when the corn was stressed during the pollination period.

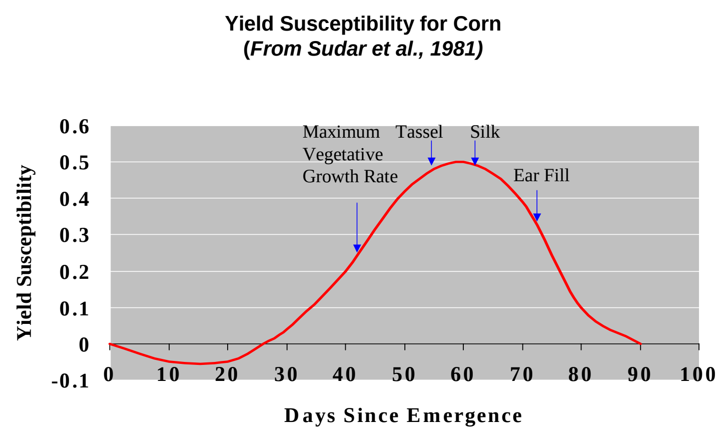

Figure 5. Yield susceptibility for corn.

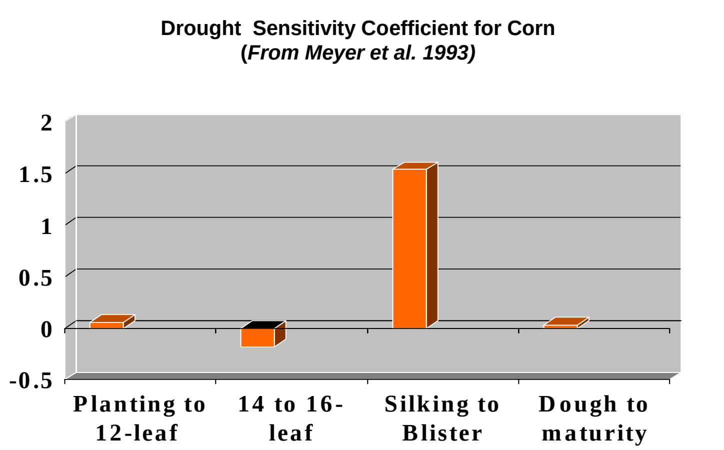

Figure 6. Drought sensitivity coefficient for corn.

The research found that a water savings of more then 4 inches or about 30 percent could be achieved without a significant yield reduction if the water was withheld only during the vegetative period and if the plots were then fully irrigated during the rest of the growing season. On-farm studies have shown that 1-3 inches of irrigation water can be saved as compared to the Fully Watered strategy. However, during springs and early summers with above normal precipitation, no water savings should be expected.

Starting in the early 1980's, this idea was confirmed by further research conducted at North Platte, both using a solid-set sprinkler irrigation system and under surface irrigation. (Schneekloth et al. 1991)

The long and short of it is that corn yields are not very sensitive to moisture stress before the tassel stage or after the dough stage, however, from the silking to the blister stages corn is extremely sensitive. All irrigation strategies should focus on minimizing moisture stress during this time. Figures 5 (From Sudar et al., 1981) and 6 (From Meyer et al. 1993) are examples of two curves that have been developed to show how moisture stress effects corn yields as the crop progress though the season.

The Water Miser BMP allows a 50 percent depletion of the plant available water during the critical growth stages. However, a strong case could be made for only allow a 40 percent depletion during this stage because corn is very susceptible to

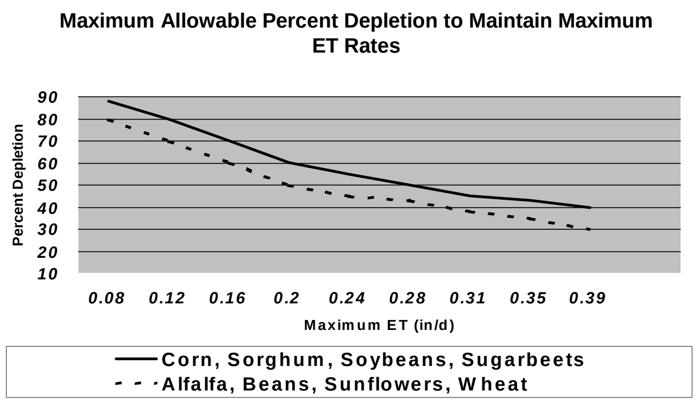

Figure 7. The maximum allowable percent depletion of the soil water that will still maintain maximum ET rates.

moisture stress during this time and water use is high, which would make any delay in irrigation cause a significant yield loss. Further support for the 40 percent number is based on the information presented in Figure 7 (modified from Doorenbos et al., 1979). It shows that on lower ET days (0.08-0.12 in/d) the soil can be very dry without having any moisture stress occurring. However, on high ET days (0.35-0.39 in/d) the field can only have 40 percent of the plant available water used or depleted without causing yield loss from moisture stress. Keeping the soil a little wetter during this time should not increase water use as long as the crop is allowed to use the extra water before maturing by cutting back on irrigation in the later parts of the growing season.

Another important point from Figure 7 is that in the early and late parts of the season when ET rates are lower, the soil needs to be very dry to create moisture stress.

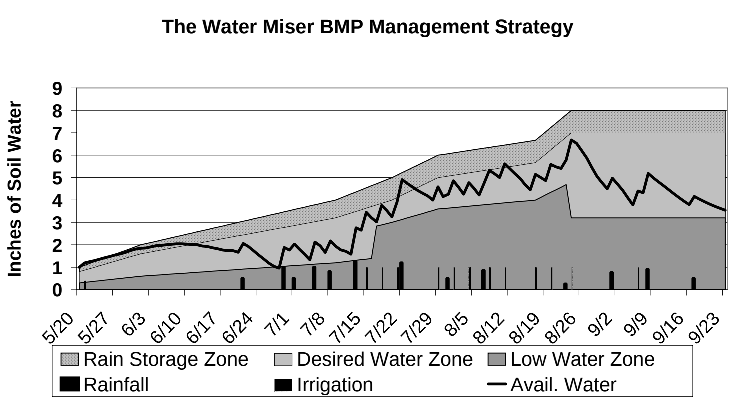

Figure 8. The gray shaded area shows desired water zone for the Water Miser BMP strategy. The black line showing available water should stay in the gray shaded area to indicate planned moisture level for the crop. Rain may push the line into the rain storage zone.

The Water Miser BMP strategy is illustrated in Figure 8. This irrigation scheduling method is sometimes called a crop growth stage irrigation strategy. Irrigation is limited during the vegetative growth stage while full irrigation management is practiced during the critical reproductive growth stages.

MANAGEMENT TIPS

Managing a field with the Water Miser BMP strategy requires good soil moisture readings and careful timing. The upper three feet of the soil profile should be at or near field capacity in the early part of the growing season so the developing roots can grow in moist soil, thus allowing the stress to come on more gradually. Most fields in west central Nebraska that were somewhat fully irrigated the previous year will meet this condition even with below normal precipitation. If the field is dry, be very careful not to over stress the corn.

The biggest hazard involved with this strategy is not getting the irrigation started soon enough to avoid excessive stress during the pollination period. If soil water reserves are depleted and something occurs to delay irrigation, severe problems could occur during the pollination period. Also, keep in mind that lower capacity systems (less then 5.5 gpm/ac) need to be started sooner, as compared to higher capacity systems (over 7 gpm/ac) which can wait to get more of this benefit, but still needs to be started soon enough to get caught up before the reproductive period starts. The above listed system capacities are net system capacities and would need to be increased by the water application efficiency of the irrigation system. (Kranz et al., 1989)

DEFICIT IRRIGATION

The deficit irrigation management strategy should only be used if the water supply is short, since it will result in reduced yields. This strategy focuses on correctly timing the application of a restricted quantity of water, both within the growing season as well as over a several year period. The intent is to stabilize yields between years by applying irrigations based on soil-water depletion. The idea is to keep the soil dry enough to significantly reduce ET, but keep it from getting so dry that it substantially lowers the yield potential. Less water will be applied during wetter years, while more will be applied through the drier years, with an average over the years equaling the available quantity of water. The management strategy is to delay the application of water until about 2-weeks before tassel emergence for corn, unless soil-water depletion exceeds 70%. Once the crop reaches the reproductive growth stage the plant available soil-water (in the active root zone) is maintained in a range between 30 and 60% depletion. It is allowed to dry down to 70% depletion after the

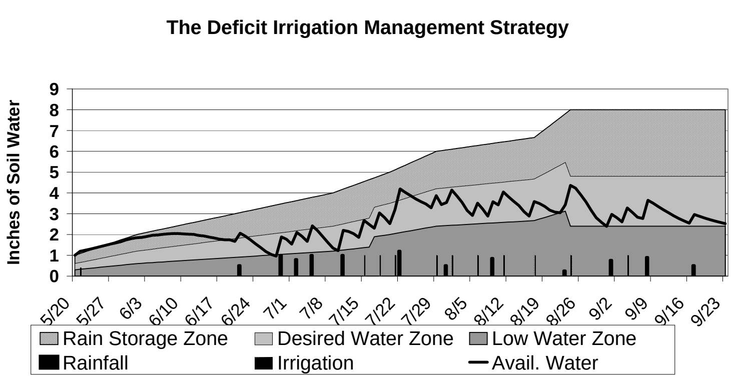

Figure 9. The gray shaded area shows desired water zone for the Deficit Irrigation strategy. The black line showing available water should stay in the gray shaded area to indicate planned moisture level for the crop. Rain may push the line into the rain storage zone.

hard dough stage. The idea is that these depletion numbers should be changed based on the amount of water the producer has to work with. More research is needed to determine guidelines for differing water use levels. Figure 9 graphically illustrates this strategy.

MANAGEMENT TIPS

The Deficit Irrigation strategy is the most challenging to manage. In fact it may be as much an art as it is science. The challenge is to keep the crop fairly dry to reduce the ET to the desired level, while preventing an extremely hot, dry few day period from significantly impacting the yield potential. Remember this strategy is intended to lower the plant water use to the amount of water available for the season, but as a consequence the yield will be lowered as well. Also, this strategy does not work with low capacity irrigation system. It only works if the restricted quantity of water can be put on the field quickly and at the right time. If the water supplies are very limited, irrigating less acres or growing a crop that requires less water may be a better option.

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PATHWAYS TO EFFECTIVE APPLICATIONS

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INTRODUCTION

Sprinkler systems, primarily center pivot systems, are widely used in the Great Plains of the United States. Methods of irrigation application using sprinklers vary considerably and include high-angle, high-pressure impact sprinklers, low-angle, medium- to low-pressure impact sprinklers, medium- to low-pressure spray nozzles, medium- to low-pressure rotary nozzles, ground-level LEPA (low-energy precision application) bubblers or drag socks or multi-mode LEPA devices (chemigation), and various LESA (low elevation spray applicators) or LPIC (low-pressure, in-canopy) application systems. Graded furrow irrigation, typically from gated pipelines, is still widely used in the Great Plains. Some of these systems utilize tailwater recovery to recirculate field runoff water. Microirrigation, especially SDI (subsurface drip irrigation), is growing in use in the Great Plains, although still not a widely adopted application technology, but one that can fit many situations with a high potential for effective irrigation. To achieve effective applications, the irrigation technology must fit the soil, crop, and irrigation water supply. Optimum irrigation water management must then be coupled with the chosen irrigation application technology to achieve effective applications to the crop.

Effective application is the terminology chosen to describe efficiency both in terms of water applications and crop productivity. In prior Central Plains Irrigation conferences (Howell, 2002; Martin, 2004), concepts of irrigation efficiency and water use efficiency were described and discussed. The purpose of this paper is to briefly outline choices for irrigation application technology and irrigation water management that can lead to *effective applications* that minimize inefficient uses of water and that can lead to near optimum crop profitability.

FRAMEWORK

The outline concepts from Purcell and Currey (2003) provide a useful tool in evaluating likely processes to achieve “effective applications.” Figure 1 illustrates the water flow pathway from its source to the crop and then through the process of obtaining a yield from the crop. In order to calculate the differences between water inputs, losses and uses, all the items in Fig. 1 must have compatible temporal and spatial scales. Determining some of the water pathway components may be difficult or highly uncertain for some time and space situations. In broad terms, this concept of effective water use is often described as "water use efficiency" (WUE) although Howell (2002) and Lamm (1997) point out the differences between WUE and irrigation efficiency (E_i) or irrigation application efficiency (E_a). For many reasons as discussed in Purcell and Currey (2003), WUE and either E_a or E_i cannot individually determine effective applications, but collectively they can distinguish irrigation technology and management that will have "effective applications."

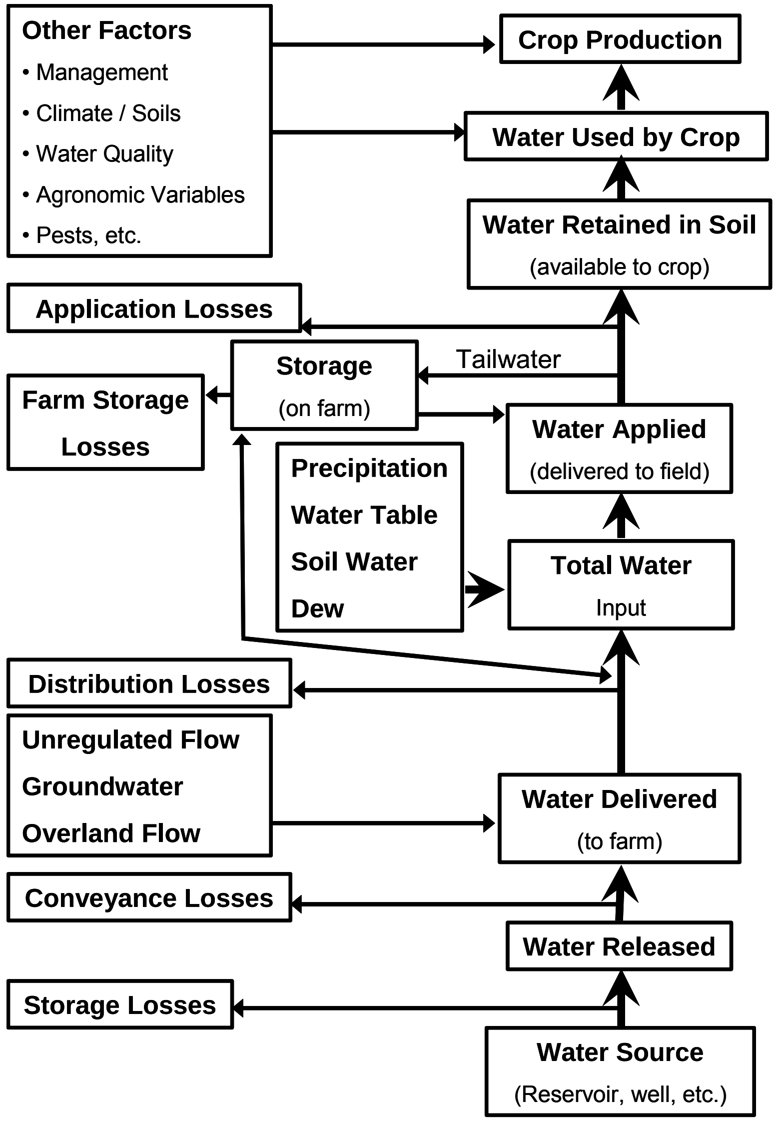

Figure 1. Illustration framework of water flow pathway from source to crop for producing yield adapted from Purcell and Currey (2003).

IRRIGATION EFFICIENCY CONCEPTS

Traditional concepts of irrigation efficiency (Heermann et al., 1990) are based on engineering concepts of the fraction of water being diverted that is then available for useful and beneficial needs of the crop. Of course, the catch in these engineering definitions is characterizing what constitutes a "required" and/or "beneficial" use of the water (Burt et al., 1997), which may be determined by outside institutions (legal or regulatory) and/or other societal issues (wetlands, wildlife habitat, etc.). Figure 2 illustrates several of the water transport components involved in defining various irrigation performance measures. The spatial scale can vary from a single irrigation application device (a siphon tube, a gated pipe gate, a sprinkler, a microirrigation emitter) to an irrigation set (a basin plot or set, a furrow set, a single sprinkler lateral, a microirrigation lateral) to broader land scales (field, farm, an irrigation canal lateral, a whole irrigation district, a basin or watershed, or a river system, or an aquifer). The time scale can vary and may include periods from as short as a single application (or irrigation set), to a part of the crop season (preplanting, emergence to bloom or pollination, reproduction to maturity), or the irrigation season, crop season, or a year, partial year (pre-monsoon season, summer, etc.), a water year (typically from the beginning of spring snow melt through the end of irrigation diversion, or a rainy or monsoon season), or even a period of years (a drought or a "wet" cycle). Irrigation efficiency affects the economics of irrigation, the amount of water needed to irrigate a specific land area, the spatial uniformity of the crop and its yield, and the amount of water that might percolate beneath the crop root zone. It can also affect the amount of water that can return to surface sources for downstream uses or to ground water aquifers that might supply other water uses, and the amount of water lost to unrecoverable sources (salt sinks, saline aquifer, or an unsaturated vadose zone). Return flow of water is not a loss in terms of the larger scale (water district, hydrologic basin, etc.) and will not reduce overall efficiency unless the water quality is unsuitable for irrigation use or the returned water is not available within the irrigation season under consideration. Spears and Snyder (2004) discuss the added energy needed to recover this return water and the concepts of efficiency on the basin scale.

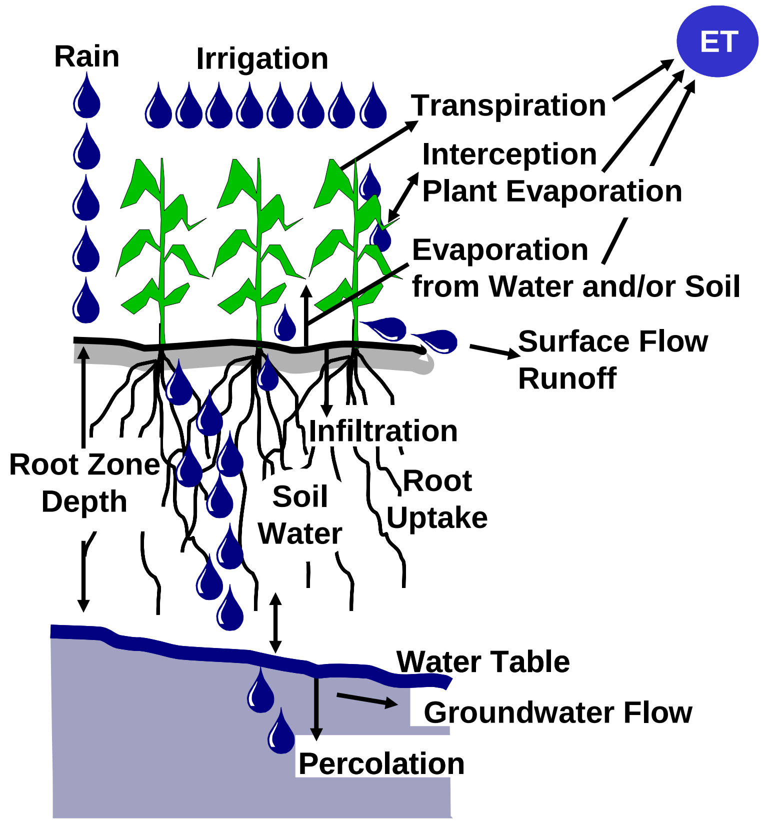

Figure 2. Illustration of various water transport components needed to characterize irrigation efficiency.

The volumes of water for the various irrigation components are typically expressed in units of depth (volume per unit area) or simply the volume for the area being evaluated. Irrigation water application volume is difficult to measure; so, it is usually computed as the product of water flow rate and time. This places emphasis on accurately measuring the flow rate. The accurate measurement of water percolation volumes, ground water flow volumes, and water uptake from shallow ground water remain nearly impossible under most circumstances.

We are prone to speak and characterize some water components as losses, although they are not lost but just unavailable for use (Fig. 1). From the water supply (reservoir, ground water aquifer, river, etc.), water can be a lost due to evaporation (e.g. evaporation from a reservoir), transpiration (e.g., water consumed by phreatophytes or weeds along the water course), vertical seepage or horizontal flow beyond the "control boundaries" (will depend on the spatial scale of interest), and any operational losses or leakages from the source that can't be recovered. From the source to the farm, there may be conveyance losses which might be evaporation from any open water conveyances (e.g., canals), leakages (e.g., vertical seepage from a canal or pipeline leaks), operational spills, as well as transpiration by phreatophytes or weeds along the water route. There could be gains in water from the release point to the farm if water is recovered from drainage ditches, groundwater inflows, as well as regional surface water recovery from runoff. Each of these water sources is subject to various State, water district, and environmental laws or regulations that might restrict their use either by permit, custom, or legal restrictions. In the Great Plains, we find limited on-farm storage of water because the majority of irrigation water is supplied directly to the farm through wells into a aquifer [usually the High Plains Aquifer or Ogallala Aquifer although some alluvial aquifers are of major importance (e.g. the Arkansas River, the South and North Platte Rivers). In some cases, small holding reservoirs are utilized with larger center pivot systems or with some microirrigation systems for short-term storage and flow regulation when several wells are needed to supply water to the field at a rate that exceeds an individual well's flow rate. In these cases, a submersible turbine pump (desired for automation reasons) or a centrifugal pump will be used to lift the water from the shallow storage reservoir (usually these are an acre or less in area with a volume capacity of 2-5 ac-ft) to the irrigation system and to provide the system operating pressurization. These on-farm storage ponds have similar potential water loss components as those discussed above for conveyance and water supply.

On the farm or field, the net irrigation supply is augmented by water sources that are specific to individual regions (e.g., rainfall or shallow water tables) and available soil water (that may be recharged from off-season precipitation). The amount of irrigation water required by the crop is the net difference between the crop evapotranspiration (ET) and the net "effective" precipitation during a specific period, and "readily" available soil water (typically defined as a portion of the stored or retained soil water between the upper limit of "field capacity" and the "wilting point"). The available water is generally a property of the soil texture (its physical particle size distribution, bulk density, mineralogy, chemical characteristics, etc.). This "net" Irrigation requirement is typically expressed as

$$I_i = ET_i - \left(Pe_i + SW_i\right) \quad \text{... [1]}$$

where I is the "net" irrigation requirement for period i, ET is the evapotranspiration during the period, Pe is the "effective" precipitation during the period, and SW is "available" soil water used (soil water depletion) during the period with all parameters expressed in units of depth (mm or in.). Equation 1 neglects or ignores percolation below the root zone and possible water table uptake, too. Various procedures are used to estimate Pe, and for simplicity at a given location (farm or field) SW might be assumed to be a constant value dependent on the soil texture at the site, the ET rate, and the length of specific period "i". The "gross" irrigation requirement is simply estimated as the "net" requirement (I) divided by an estimated or known irrigation application efficiency (E_a; expressed as a fraction).

IRRIGATION APPLICATION EFFICIENCY

Although E_a (irrigation application efficiency) is a widely used concept (Heermann et al., 1990; Howell, 2002), it also quite suspect and often difficult to know precisely (Lamm, 1997 & 2002). E_a is generally defined as the fraction of the "gross" irrigation amount that is stored in the root zone. It is determined by measuring or estimating

- "gross" application (volume/rate/time and the area irrigated)
- off-target water (drift, etc.)
- percolation below the root zone
- evaporation from applied water (wetted soil and/or foliage or droplets)
- runoff from irrigation
- infiltrated soil water
- change in water stored in the root zone

all of which are difficult to quantify precisely. In addition, the exact crop root zone may not be known precisely. The "gross" irrigation application may not be known with great precision owing to the myriad techniques utilized to either measure flow rate or volume or indirect measures (e.g., electrical power consumption, fuel consumption, etc.). Measuring soil water is nearly a complete science unto itself. If one assumes that off-target losses are minimal, we are left with what many call the "*Big Three*" losses:

- D or percolation (drainage) from the root zone
- E or evaporation, and
- Q or runoff

Effective applications must minimize these, so called "*Big Three*," losses, particularly where irrigation water costs are directly linked to the volume of water diverted (either pumped from a well or purchased from a water district). As Lamm (2002) emphasized, E_a is often misused and incorrectly used in comparing or ranking irrigation application technologies. It certainly has its place in irrigation science as a performance measure, but it is, perhaps, better utilized as a tool to indicate means to improve specific irrigation systems rather than a tool to judge systems. Certainly, specific irrigation application technologies will have a "potential" to be more efficient than other technologies. But, a conversion from one technology to another solely to improve efficiency is usually "suspect", as far as "saving water", without a concurrent irrigation water management technology or training investment.

Percolation Losses

Percolation losses are more easily controlled with the smaller, more frequent applications from center pivot systems or SDI (or microirrigation, in general) compared with the typically larger, less frequent surface irrigations. However, even SDI can have significant percolation losses from the root zone if not managed carefully (Darusman et al., 1997a & 1997b). Surge flow furrow irrigation has been one of the more effective technologies to reduce excessive infiltration and percolation with graded furrow systems (Allen and Schneider, 1992; Musick et al., 1987). Furrow packing or "slicking" has been used effectively with graded furrow irrigation to reduce excessive infiltration (Allen and Musick, 1992; Allen and Schneider, 1992). PAM (Polyacrylamide) polymers have been effective in reducing graded furrow percolation losses (Lentz et al., 2001).

Even if no apparent percolation loss is perceived from smaller, frequent applications, surface redistribution from higher application rate technologies (LESA, LPIC, LEPA, etc.) can result in "potential" percolation losses in lower lying areas that might accumulate runoff. Besides the loss of water available to the crop, percolation losses invariably also include nutrient leaching that can reduce available crop nutrients within the root zone, which increases costs for crop nutrients (fertilizers) and has water quality and environmental concerns.

Evaporation Losses

Evaporation losses are reduced by not irrigating bare soil, using alternate furrow irrigation, lowering center pivot system applicators nearer the ground to reduce wind effects together with utilizing various choices of spray/rotator plate deflectors (flat, grooved, concave, convex, etc.), sprinkler applicators, spacing, etc. (Howell, 2004) together with optimum operating pressure for the nozzle size to reduce small droplets. Sprinkler evaporation losses, particularly for center pivot systems, are generally perceived to be greater than measurements indicate [see Howell et al. (1991) for a current review up to that time, and Schneider (2000) for a later review]. Tolk et al. (1995) and Thompson et al. (1997) discuss measurements and modeling of center pivot system water losses from evaporation in more detail. However, for “gross” applications of 25 mm (1.0 in.), evaporative losses from center pivot systems with sprinklers or spray heads can as large as 10 to 20% of the applied water depending on the specific circumstances of the application. LEPA applications under “optimum” cases (e.g., good furrow dikes, alternate row applications with drag socks, circular rows for a center pivot system, etc.) may be less than 5-6% of the application amount. The main evaporation loss from most sprinkler or spray technologies is the “net” canopy evaporation, which is influenced by the wetting duration. The wetting duration depends on distance from the center pivot point and “gross” application amount, and on the wetted diameter of the application technology (e.g., pipeline low-angle impact sprinklers may have wetted diameters greater than 9 to 30 m or 15 to 100 ft). Of course, end guns will have a much greater “potential” evaporation loss (when operating; even if just operated in the corners) due to both the larger wetted diameter of the end gun and the greater droplet transit times and greater exposure to the wind/atmospheric factors. In order to spread evaporative losses evenly around the field, the center pivot irrigation frequency (or full rotation time) is generally desired to be a non day integer (e.g., not 24, 48, or 72 hrs), but a fraction of an even day integer so the system will irrigate differing zones of the field at the same time of the diurnal cycle (e.g., 38, 54, etc. hrs per revolution).

Crop residues effectively reduce evaporation from the soil. They also improve soil tilth and, generally, increase infiltration if the residue mass amount is significant (~3 to 4 Mg ha^{-1} or 1.5 to 3 tons ac^{-1}). Ridge till or strip till has been effective in preserving soil cover using previous crop residues while utilizing a reduced or conservation tillage system.

Runoff Losses

Runoff from graded furrow systems can exceed 30 to 60% of the applied water (Lentz et al., 1992). PAM (Polyacrylamide) polymers have been effective in reducing the runoff fraction of surface irrigation (Lentz et al., 1992; Lentz et al., 2001) but sometimes at the expense of increased percolation losses. Runoff with surface irrigation and center pivot systems (Schneider and Howell, 2000) can be a significant loss of water and cause ineffective applications. Generally, no irrigation runoff should occur with SDI or microirrigation unless a pipeline leaks or breaks. LEPA requires surface storage from furrow dikes or dammer diker implements to provide temporary surface storage for application volumes that exceed the soil infiltration capacity (Kincaid et al., 1990; Kranz and

Eisenhauer, 1990; Coelho et al., 1996; Howell et al., 2002). Furrow diking and dammer diking serve dual purposes in storing irrigation applications as well as rainfall (Lyle and Dixon, 1977; Jones and Stewart, 1990) for infiltration and reducing/eliminating runoff from the field. It is a well known practice in dryland cultures (Jones and Clark, 1987). Furrow diking can be particularly important with center pivot systems when deficit irrigation is planned or water deficits result from regional/local droughts when irrigation capacity (irrigation volume per unit area) is insufficient to meet the crop irrigation need. Figure 3 illustrates the potential surface storage needed for impact sprinklers and LESA/LPIC with center pivot systems. Systems with high instantaneous application rates, particularly LEPA, LESA, or LPIC systems, must utilize a surface storage tillage technology or an effective conservation tillage system (e.g., ridge till or strip till) to minimize surface water redistribution and possible runoff or percolation from down slope areas.

IRRIGATION WATER MANAGEMENT

Irrigation water management is the integration of irrigation scheduling or automation with the application technology. Basically, irrigation scheduling is making decisions on irrigation timing and irrigation amount subject to the irrigation supply constraints (legal and physical) in concert with the operational constraints (labor, crop cultural operations, etc.). The goal is often to produce the greatest profit within the land, labor, capital, and water restrictions of the farm or operation.

Water Balance

Most irrigation scheduling involves the application of Eqn. 1 to estimate the irrigation amount needed to refill a portion of the soil water reservoir. The irrigation amount is constrained by both the irrigation capacity (gpm ac^{-1} or mm d^{-1}) [also considering the irrigation frequency or interval] and the irrigation application technology. Most irrigation timing decisions are based on estimated (modeled) or measured soil water. By recognizing that in Eqn. 1 that $SW = \bar{\theta}_k - \bar{\theta}_j$, Eqn. 1 can be rearranged as follows:

$$\bar{\theta}_k = \bar{\theta}_j + Pe_i + I_i - ET_i \qquad \text{... [2]}$$

where $\bar{\theta}_k$ is the mean or total "available" soil water within the root zone on the end day "k" of period "i", $\bar{\theta}_j$ is the mean or total "available" soil water on the beginning day "j" of the period, and Pe_i, I_i, and ET_i were previously defined. All terms in Eqn. 2 are in depth units (mm or in.). Typically, $\bar{\theta}_j$ is taken as $\bar{\theta}_{fc}$ (water content of the root zone at "field capacity") minus a desired soil water storage term to allow intermediate rainfall storage to minimize runoff and/or percolation. The

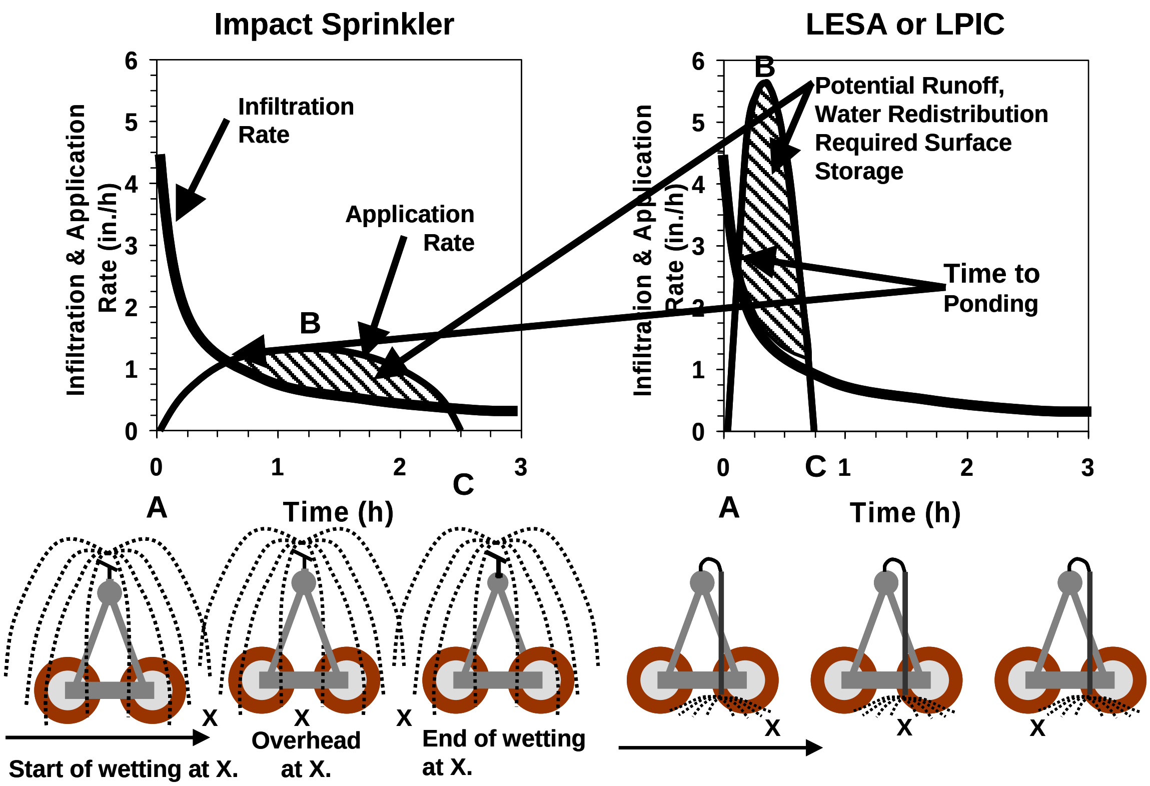

Figure 3. Illustration of runoff or surface water redistribution potential for impact sprinkler and spray (LESA or LPIC) center application packages for an example soil. (A) represents the start of the irrigation, (B) is the peak application rate (usually when the system is directly overhead), and (C) is the completion of the irrigation. The first intersection point of the infiltration curve and the application rate curve represents the first ponding on the soil surface.

goal of most irrigation decisions is to maintain the root zone soil water within the defined limits given as

$$\left(\bar{\theta}_{fc} - C\right) \geq \bar{\theta} \geq \bar{\theta}_c \qquad \text{... [3]}$$

where C is the allowed storage for intermediate rainfall and $\bar{\theta}_c$ is a “critical” lower limit of soil water that will reduce yield or crop quality. The value of $\bar{\theta}_c$ depends on the soil texture and other factors such as crop growth stage, atmospheric water demand, etc. (Lamm et al., 1994; English et al., 1990). For lighter textured soils (e.g., sands, loamy sands, or sandy loams), C may be very small or impractical to utilize due to the lower “available” soil water content.

Martin et al. (1990) defined the irrigation dates in the terms of "earliest date" [irrigation depth typically applied will just refill the root zone without excessive runoff or percolation] and the "latest date" [amount if irrigation was delayed until θ was near θ_c]. Both of these irrigation dates bracket the optimum irrigation timing decision date expressed as $D_e \leq D_o \leq D_l$, where the subscripts denote "e" for early, "o" for optimum, and "l" for latest. The decision to postpone irrigations from D_e to D_l considers rainfall forecasts, ET rates, labor and farm operation decisions and the risk assumed by the producer. As the date is postponed to near D_l, some reduction in yield may be anticipated.

SUMMARY

Effective irrigations must consider the application technology and the irrigation water management. Table 1 gives an outline of technologies that can be effective in achieving irrigations that are aimed to achieve high profits within producer constraints. No single irrigation application technology or management technology will insure "effective applications", but an integration of "Best Management Practices" (BMPs) involving technology and management can offer pathways to achieve "effective applications" and wise utilization of our limited water supplies for profitable irrigated agriculture.

Table 1. Example irrigation concepts for “effective applications” emphasizing “Big Three” water loss components.

IRRIGATION TECHNOLOGY			
Surface Irrigation			
Surge Flow	Percolation	+[†]	Reduced by more uniform infiltration “opportunity” times
	Evaporation		
	Runoff	+	Reduced by runoff flows and “cut-back” controls
	This technology has relatively low costs and can be easily adopted into most existing gated pipe systems.		
Tailwater Recovery	Percolation	+ -	Reduces field percolation but greater seepage losses from reservoir.
	Evaporation		
	Runoff	+	Recycles runoff water.
	This technology can be adopted for most furrow systems, but it adds additional pumping and capital costs to return the water.		
PAM (Polyacrylamide)	Percolation	+	Reduced by more uniform infiltration “opportunity” times
	Evaporation		
	Runoff	+	Reduced by reduced flows and “cut-back” controls
	This technology is relatively low cost, although repeated applications may be required, and is easily adopted to most furrow systems.		
Center Pivot Sprinkler Irrigation			
Low-Angle Impact Sprinklers	Percolation	+	Reduced by lowered application amounts.
	Evaporation	+	Reduced by lowered wind effects.
	Runoff	+	Reduced by usually having a lower peak application rate.
	Easily adopted to existing high angle sprinkler systems.		
Low Pressure Applicators	Percolation	-	In some cases, can have significant surface water movement.
	Evaporation	+	Reduced by having smaller wetted diameter and selection options for spray applicators, plate grooves, and groove shapes.
	Runoff	-	Increased if reduced wetted diameter and higher peak application rate exceed soil infiltration and surface storage capacity.
	Moderate capital costs if retrofitting older machines with wider drop spacing and greater number of heads that are more closely spaced.		

[†] The “+” symbols indicate a generally recognized practice to reduce losses for that component and the “-” symbol indicates either no improvement or possibly greater loss for that component.

<table>
<tr><td colspan="4">Table 1. Part II.</td></tr>
<tr><td colspan="4">IRRIGATION TECHNOLOGY</td></tr>
<tr><td colspan="4">Center Pivot Sprinkler Irrigation, continued</td></tr>
<tr><td rowspan="4">LEPA</td><td>Percolation</td><td>+</td><td>Reduced by lowered application amounts.</td></tr>
<tr><td>Evaporation</td><td>+</td><td>Reduced by reduced wetted area (minimal canopy wetting).</td></tr>
<tr><td>Runoff</td><td>+
-</td><td>Reduced if furrow dikes retain all applied water. Can be a significant water loss if dikes can't contain the applied water.</td></tr>
<tr><td colspan="3">Easily adapted to newer pivots with closely spaced outlets. Can add increased costs for the greater number of applicator heads and diking machinery. Requires furrow diking and circular planting to be most effective.</td></tr>
<tr><td rowspan="4">LESA / LPIC</td><td>Percolation</td><td>+</td><td>Reduced by lowered application amounts.</td></tr>
<tr><td>Evaporation</td><td>+</td><td>Reduced by reduced wetted area.</td></tr>
<tr><td>Runoff</td><td>-</td><td>Can be a significant water loss if reduced wetted diameter and higher peak application rate exceed soil infiltration and surface storage capacity.</td></tr>
<tr><td colspan="3">Easily adapted to newer pivots with closely spaced outlets. Can add increased costs for the greater number of applicator heads and diking machinery, if needed. Easily compatible with conservation tillage systems when diking not required or furrow dikes used with ridge till.</td></tr>
<tr><td colspan="4">Microirrigation</td></tr>
<tr><td rowspan="4">SDI</td><td>Percolation</td><td>+
-</td><td>Reduced by lowered application amounts, but can be a significant loss if water profile is maintained at a high soil water content.</td></tr>
<tr><td>Evaporation</td><td>+</td><td>Reduced by smaller wetted area (only water that moves upward readily can evaporate.</td></tr>
<tr><td>Runoff</td><td>+</td><td>Reduced by lowered application amounts.</td></tr>
<tr><td colspan="3">Technology is rapidly advancing. It remains relatively expensive but is easily automated. Adaptable with ridge till and/or strip till systems. Fits odd or irregular shaped fields.</td></tr>
<tr><td colspan="4">TILLAGE TECHNOLOGY</td></tr>
<tr><td rowspan="4">Ridge Till</td><td>Percolation</td><td></td><td></td></tr>
<tr><td>Evaporation</td><td>+</td><td>Reduced by crop residues shading the soil and by reduced heating of the soil.</td></tr>
<tr><td>Runoff</td><td>+</td><td>Reduced by crop residues enhancing soil infiltration rates ad increasing surface detention water storage.</td></tr>
<tr><td colspan="3">Requires planting and cultivating machinery retrofitting or changing. May require some individual equipment adoptions. Adapted to SDI as well as LEPA/LESA/LPIC.</td></tr>
</table>

Table 1. Part III.			
TILLAGE TECHNOLOGY, *continued.*			
Strip Till	Percolation		
	Evaporation	+	Reduced by crop residues shading the soil and by reduced heating of the soil.
	Runoff	+	Reduced by crop residues enhancing soil infiltration rates ad increasing surface detention water storage.
	Requires planting and cultivating machinery retrofitting or changing. May require some individual equipment adoptions. Well adapted to LESA/LPIC but can be used effectively with SDI.		
WATER MANAGEMENT TECHNOLOGY			
Irrigation Scheduling			
ET Based	Percolation	+	Reduced by decisions to time and size events to match soil water holding capacity.
	Evaporation	+	Reduced by using a later day scheduling timing to lengthen event cycles.
	Runoff	+	Reduced by using timing to consider rainfall probabilities.
	Easily adapted to all irrigation application technologies. Requires training and field observations and measurements. Can be contracted through private consultants.		
Soil Sensor Based	Percolation	+	Reduced by decisions to time and size events to match soil water holding capacity. Can actually monitor lower root zone.
	Evaporation	+	Reduced by using a later day scheduling timing to lengthen event cycles.
	Runoff	+	Reduced by automated irrigation shut-down.
	Easily adapted to all irrigation application technologies. Requires modest to significant capital investment and some training. Can be contracted through private consultants. Can be easily integrated with center pivots or SDI into automated controls.		
Plant Sensor Based	Percolation		
	Evaporation	+	Reduced by using a later day scheduling timing to lengthen event cycles.
	Runoff		
	Easily adapted to most irrigation application technologies. Requires modest capital investment and some training. Can be contracted through private consultants. Can be integrated with center pivots or SDI into automated controls.		

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IMPACT OF WIDE DROP SPACING AND SPRINKLER HEIGHT FOR CORN PRODUCTION

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Introduction

Using center pivot sprinkler nozzles below the top of the corn crop canopy presents unique design and management considerations. Distortion of the sprinkler pattern can be large and the resultant corn yield can be reduced. In many areas, water available for irrigation is being limited due to reduced supply of both ground and surface water. During periods of drought, uniformity problems associated with center pivot irrigation become quite visible. Many times water stress on the crop is not evident until late in the season when the crop has nearly matured. In many cases aerial observations of fields have revealed concentric rings that corresponded to sprinkler spacing (Figures 1a - b).

Figure 1a. Height reduction in corn caused by drops spaced too wide.

Figure 1b Concentric rings in corn field caused by having drops spaced too wide.

The impact of sprinkler spacing on water distribution and corn yield was the focus of University of Nebraska and Kansas State research studies. Researchers conducted field experiments along with on-farm evaluations to gain a better understanding of operating sprinkler devices within the corn canopy. The results from these experiments will be discussed.

Field Evaluation of Changes in Soil Water Content

In a Nebraska study soil water content was measured as a method to evaluate the uniformity of water distribution. Soil water content was measured in the top 12 in. of soil before and after irrigation. Spinners[1] were spaced 12.5 ft apart and located at a height of 42 inches in a mature corn crop. Sprinklers were moving parallel to the corn rows but not necessarily between the corn rows. Figure 2 shows the location of the sprinklers in the corn rows and the change in soil water content measured before and after irrigation. Soil water content increased nearly 12% in the rows nearest the sprinkler device. Soil water content averaged less than a 2% increase at locations directly between the sprinkler devices. The small change in soil water content indicates the rows between the sprinkler devices received little or no water during the irrigation event.

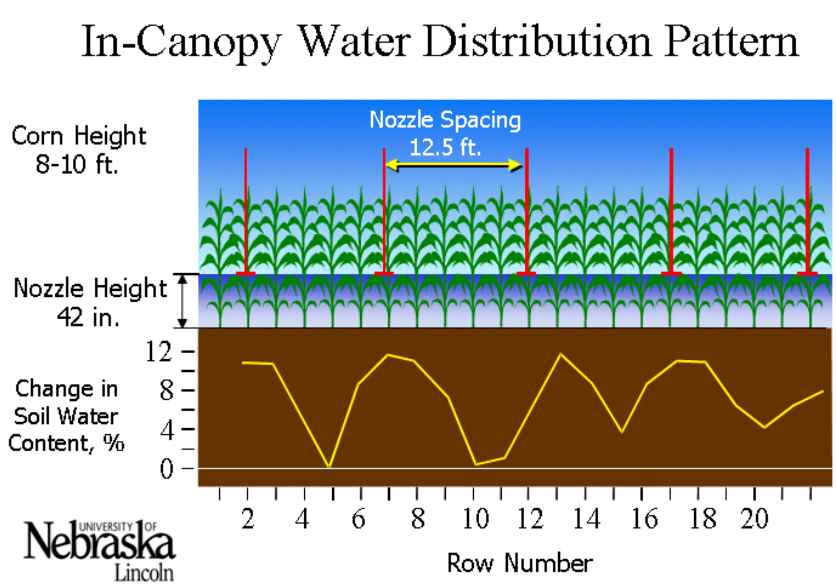

Figure 2. Changes in water content following irrigation with sprinkler nozzles located in a corn canopy.

[1]Mention of trade name is for information only and does not imply endorsement

Variation in Corn Yield as Affected by Sprinkler Height

When the sprinkler pattern is distorted and the nozzle spacing is wide enough to prevent some corn rows from getting equal opportunity to water, yields can be reduced. A study was conducted at the KSU Northwest Research-Extension Center from 1996-2001 to examine the effect of irrigation capacity and sprinkler height on corn production when the spray nozzle spacing was too wide for adequate in-canopy operation (10 ft instead of more appropriate 5 ft spacing). Performance of the various combinations was examined by measuring row-to-row yields differences (i.e. Row yields 15 inches from the nozzle and 45 inches for the 10 ft nozzle spacing.) Corn rows were planted circularly allowing the nozzle to remain parallel to the corn rows as the nozzle traveled through the field. As might be expected, yield differences were greatest in dry years and nearly masked out in wet years. For the purpose of brevity in this report, only the 6 year average results will be reported. Even though the average yield for both corn rows was high, there is a 16 bu/acre yield difference between the row 15 inches from the nozzle and the corn row 45 inches from the nozzle for the 2 ft nozzle height and 10 ft nozzle spacing (Figure 3). At a four ft nozzle height the row-to-row yield difference was 9 bu/acre and at the 7ft height the yield difference disappeared. This would be as expected since pattern distortion was for a shorter period of time for the higher nozzle heights. It should be noted that the circular row pattern probably represents the least amount of yield reduction, since all corn rows are within 3.75 ft of the nearest nozzle. For straight corn rows, the distance for some corn plants to the nearest nozzle is 5 ft.

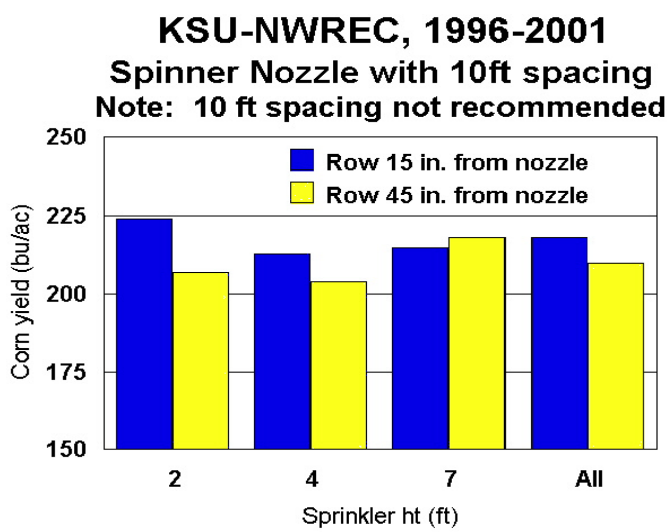

Figure 3. Row-to-row variation in corn yields as affected by sprinkler height in a study with a nozzle spacing too wide (10 ft) for in-canopy irrigation, Colby, Kansas. Data averaged across 4 different irrigation levels. Note: The average yield for a particular height treatment would be obtained by averaging the two row yields.

On-Farm Evaluation of Sprinkler Spacing

Many center pivot sprinkler systems are designed with wide sprinkler spacing as a method to reduce equipment cost. For outer spans closer sprinkler spacing is needed in order to meet the water application requirements. Although concentric rings were showing up in Nebraska fields, the outer portions of the fields showed no such pattern. To evaluate the rings, a series of samples were collected to determine crop yield and soil water content. Samples were collected from both sprinkler spacings where the spacing transition occurred to insure similar soil type and cultural conditions.

The location of sprinklers were first identified in relation to the wheel tracks. Then the location of sprinklers were superimposed in that area of the field where the center pivot sprinkler devices run nearly parallel with the planted rows of corn. All corn rows between two sprinkler devices were sampled to determine soil water content and grain yield. Yield was determined by harvesting 10 feet of row. Soil water content was measured to a depth of 4 feet at one location in each row. The results given are the average of two yield and soil water content samples.

Field measurements were collected for two different center pivot fields represented in figures 4 and 5. Sprinklers were located at a height of 7 ft. and at either a 9 or 18 ft. spacing. Corn rows were planted 30 in. apart. Figures 4a and 5a shows the results for the narrow spacing of the two fields while figures 4b and 5b show results for the wide sprinkler spacing.

Generally, there were no reasonable patterns for either yield or soil moisture content for the 9 ft. sprinkler spacing in figures 4a and 4b. However, corn yield did decline when the sprinkler spacing increased to 18 ft. in figures 5a and 5b. Because soil water data was collected at the end of the season when the crop was mature, some of the difference, or lack of difference, in soil water content may have been eliminated with late season precipitation or added irrigation. It should also be noted that soil water content is extremely low and most likely approaching wilting point.

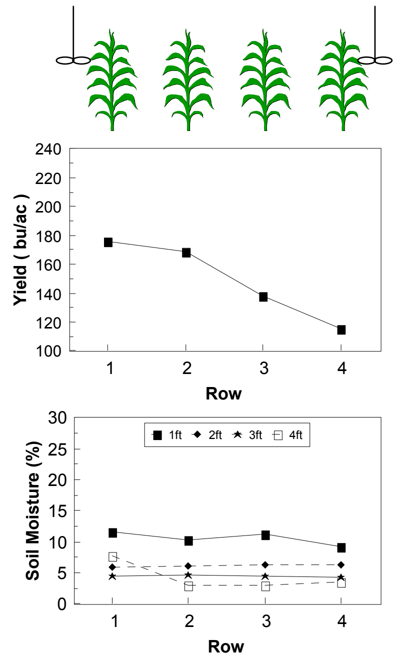

Figure 4a. Corn yield and soil water content for sprinkler devices spaced 9 ft apart at 7 ft height.

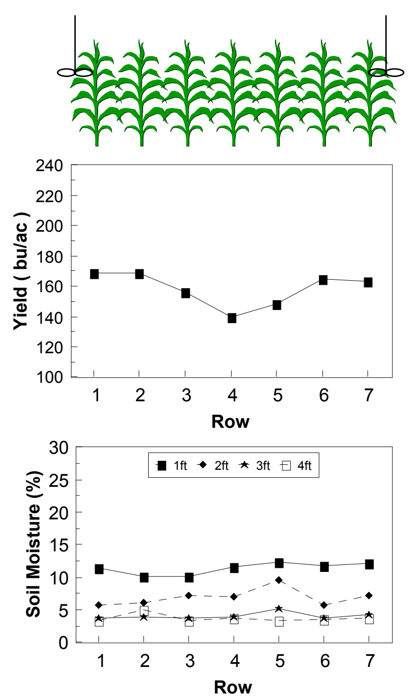

Figure 4b. Corn yield and soil water content for sprinkler devices spaced 18 ft apart at 7 ft height.

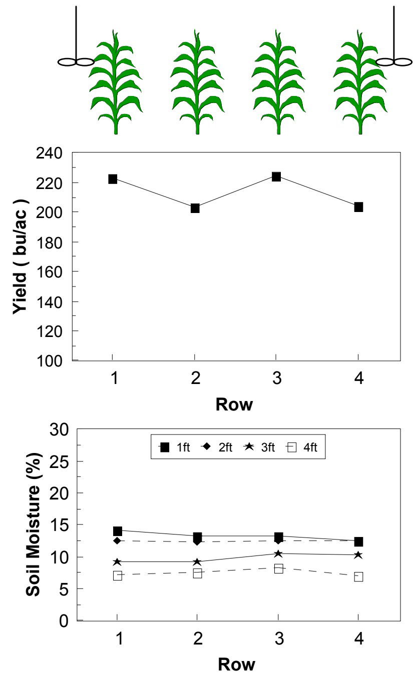

Figure 5a. Corn yield and soil water content for sprinkler devices spaced 9 ft. apart at 7 ft height.

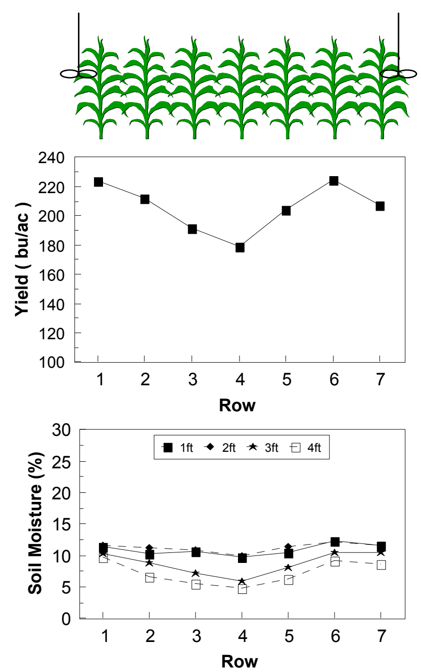

Figure 5b. Corn yield and soil water content for sprinkler devices spaced 18 ft. apart at 7 ft height.

Effect of sprinkler height and type on corn production

Another study conducted from 1994-95 at the KSU Northwest Research-Extension Center examined corn production as affected by sprinkler height and type and irrigation capacity. Spray nozzles on the span (14 ft), spray nozzles below the truss rods (7 ft) and low energy precision application (LEPA) nozzles (2 ft) were compared under irrigation capacities limited to 1 inch every 4, 6, 8 or 10 days.

Corn yields averaged 201, 180, 164, and 140 bu/a for irrigation capacities of 1 inch every 4, 6, 8, or 10 days, respectively. No statistically significant differences in corn yields, or water use efficiency were related to the sprinkler package used for irrigation. There was a trend for the (LEPA) package to perform better than spray nozzles at limited irrigation capacities and worse than the spray nozzles at the higher irrigation capacities (Figure 6).

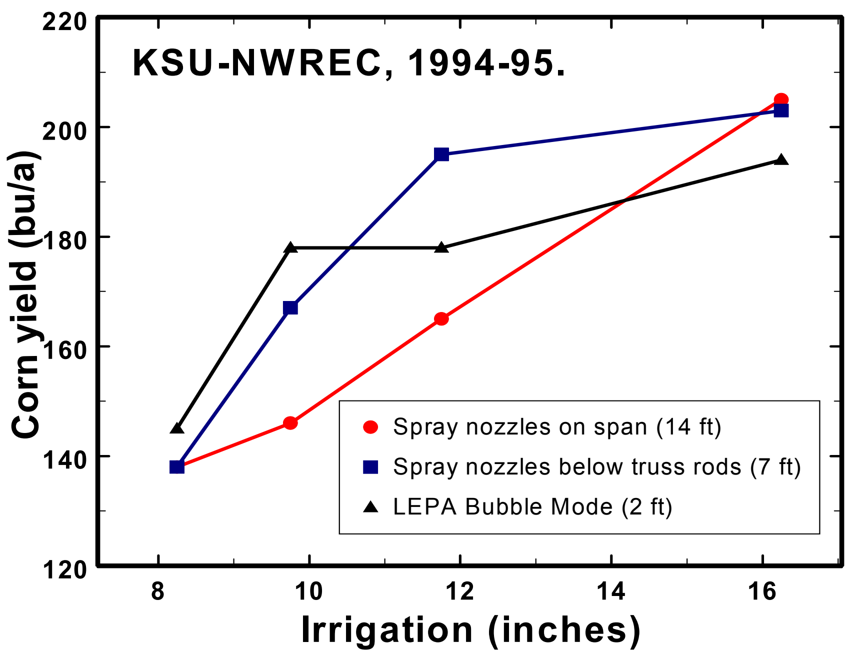

Figure 6. Corn grain yields as affected by sprinkler height and type at four different irrigation levels, KSU Northwest Research-Extension Center, Colby, Kansas, 1994-1995.

The first observation is supported by research from other locations, which shows that LEPA can help decrease evaporative water losses and thus increase irrigation efficiency. The second observation indicates that LEPA may not be suited for higher capacity systems on northwest Kansas soils, even if runoff is controlled as it was in this study. It should be noted that this study followed the true definition of LEPA with water applied in bubble mode to every other row.

The term LEPA is often misused to describe in-canopy spray nozzle application.

The reason that LEPA is not performing well at the higher irrigation capacities may be puddling of the surface soils, leading to poor aeration conditions. However, this has not been verified. In 1995 with a very dry late summer, LEPA performed better than the other nozzle orientations at the lower capacities and performed equal to the other orientations at the higher capacities. Averaged over the two years, the trend continued of LEPA performing better at the lower irrigation capacities. Overall, spray nozzles just below the truss rods performed best at the highest two capacities, but LEPA performed best when irrigation was extremely limited.

Conclusions

As the cost of pumping increases and water supplies become more restricted, irrigation schedules that more closely match water application to water use will exaggerate the nonuniform application of water due to sprinkler spacing and in-canopy operation of sprinkler devices with similar results to what we have shown here.

It has been a common practice for several years to operate drop spray nozzles just below the center pivot truss rods. This results in the sprinkler pattern being distorted after corn tasseling. This generally has had relatively little negative effects on crop yields. The reasons are that there is a fair amount of pattern penetration around the tassels and because the distortion only occurs during the last 30-40 days of growth. In essence, the irrigation season ends before severe deficits occur. Compare this situation with sprinklers operated within the corn canopy that may experience pattern distortion for more than 60 days of the irrigation season. Assuming a 50% distortion for sprinklers beginning 30 days earlier, it would result in irrigation for some rows being approximately 40% less than the needed amount. These experiments have shown that significant yield reductions do occur because of the extended duration and severity of water stress.

INFLUENCE OF NOZZLE PLACEMENT ON CORN GRAIN YIELD, SOIL MOISTURE, AND RUNOFF UNDER CENTER PIVOT IRRIGATION

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Maximizing irrigation efficiency is of enormous importance for irrigators in the Central Great Plains to conserve water and reduce pumping costs. High temperatures, frequently strong winds and low humidity increase the evaporation potential of water applied through sprinkler irrigation. Thus, many newer sprinkler packages have been developed to minimize water losses by evaporation and drift. These systems have the potential to reduce evaporation losses as found by Schneider and Howell (1995). Schneider and Howell found that evaporation losses could be reduced by 2-3% as compared to above canopy irrigation. Many producers and irrigation companies have promoted placing sprinklers within the canopy to conserve water by reducing the exposure of the irrigation water to wind. However, runoff losses can increase as the application rate exceeds the soil infiltration capacity with a reduced wetted diameter of the spray pattern within the canopy. Schneider and Howell (2000) found that furrow dikes were necessary to prevent runoff with in-canopy irrigation.

In 2003 and 2004, a study was conducted comparing sprinkler nozzle placement near Burlington, Colorado in cooperation with a local producer. The objective of this study was to determine the impact of placing the sprinkler devices within the canopy upon soil moisture, runoff and crop yield. A secondary objective was to determine the usefulness of in-season tillage on water intake and preventing runoff.

METHODS

For this study, we utilized the current configuration of a center pivot irrigation system owned by our cooperating farmer. This configuration included drop nozzles with spray heads at approximately 1.5 feet (in-canopy) above the ground surface. The sprinkler heads on the seventh and outside span of the center pivot were raised to approximately 7 feet above ground level (above canopy). This nozzle height allowed for an undisturbed spray pattern for a majority of the growing season. The sprinkler heads on the sixth span of the center pivot remained at the original height (in-canopy). In 2003, the nozzles were raised by attaching the flexible drop hose to the center pivot using truss rod slings. Because the farmer decided not to irrigate this field in 2003, we moved to an adjacent pivot in 2004. We raised the pivot nozzles by replacing the drop hoses and 'j-tubes' on this system. In 2004 the nozzle heights in the outside span were left at 1.5 feet above ground level and the next span into the field were raised to 7 feet. Spacing was 5-feet between nozzles for both site-years.

For the 2003 growing season, three in-season tillage treatments were replicated three times under each of the sprinkler heights. The three tillage treatments were cultivation, inter-row rip and basin tillage. The cooperating farmer implemented the tillage treatments when the corn was at the V6 growth stage. The tillage treatments were implemented in strips running the length of the field. The field was planted perpendicular to the sprinkler direction. In 2004, the cooperating farmer chose to use grow the corn crop using no-till and planted in a circular pattern. Although we intended to implement the inter-row rip and basin tillage operations, it was prevented by wet weather in June. Thus, the only tillage in 2004 was no-till. The cooperating farmer conducted all field operations (planting, fertilization, pest control, irrigation, etc.) during 2003 and 2004.

Runoff was measured on cultivation and basin tillage for 2 replications and both sprinkler heights in 2003. Four-inch, V-notch furrow weirs were installed at the bottom of the 8-row plots. The runoff for two 30-inch rows for the entire length of the pivot span (plot) was directed into the weir by furrows created during the tillage treatments and by soil berms where needed. The water level height in the stilling-wells of the weirs was recorded using auto-logging pressure transducers. Because the cooperating farmer chose no-till for the 2004 season, we installed two 10-foot by 32-foot runoff plots using landscape edging. Furrow weirs were installed on the lower end of the plots to measure runoff.

The soil type at both site-years was Kuma Silt Loam. The slope was approximately 1 to 1.5 percent and was fairly uniform across treatments. We measured soil moisture from mid-June through early September using a Troxler neutron probe at one-foot increments to five feet of soil depth. A neutron access tube was installed in each tillage and nozzle height treatment in 2003 and six access tubes were installed in each nozzle height treatment in 2004.

RESULTS

Grain Yield

Grain yields in 2003 were not significantly different for in-canopy and above canopy irrigation (Tables 1 and 2). Statistically significant differences between tillage treatments were also not found. However the yields for above canopy irrigation were consistently 4 bushels per acre greater than in-canopy irrigation within each tillage treatment. This would indicate that moisture stress did not occur under either above canopy or in-canopy irrigation. Grain yields for above canopy sprinkler placement were not statistically greater than in-canopy placement in 2003 as well. However, grain yields averaged across tillage treatments over the two year period suggest that a potential trend of yield advantage for above canopy placement of sprinklers over in-canopy placement. We plan to continue measuring grain yield and soil moisture at this site in 2005 to determine if this potential yield trend continues.

Soil Moisture

We measured declining soil moisture for both above canopy and in-canopy sprinklers during the 2003 growing season. When comparing above canopy to in-canopy irrigation, changes in soil moisture were greater for in-canopy irrigation than above canopy (Figure 1). The depletion of soil moisture was significantly higher for the in-canopy sprinkler placement than with above canopy sprinklers. With similar yields, this would indicate that greater runoff losses occurred with in-canopy irrigation since soil moisture usage offset reduced infiltration. The greatest difference in change in soil moisture between above and in canopy irrigation occurred during early August when the difference was greater than 3 inches of soil moisture between the two sprinkler placements. Differences in soil moisture usage at physiological maturity were 1.7 inches greater for in-canopy irrigation than above canopy irrigation.

Changes in soil moisture between tillage treatments in 2003 were not significantly different from each other within a sprinkler height during the growing season. This would indicate that sprinkler height was the dominant factor in soil moisture content.

Contrary to 2003, soil moisture initially increased early in the 2004 growing season, declining after drier weather and higher ET rates began in July. Soil moisture content initially showed a greater increase for in-canopy placement as compared to above canopy placement (Figure 2). Much of this was due to the in-canopy placement being drier at the beginning of the season and above canopy placement reaching field capacity in mid-July. Most likely, deep percolation occurred in the above canopy placement while stored soil moisture increased for the in-canopy placement. Changes in soil moisture for both in-canopy and above canopy placement were similar after July 27. This was after the above canopy and in-canopy placement reached maximum stored soil moisture during the growing season.

Runoff

Season long runoff under center pivot irrigation proved challenging to measure with the equipment available. Due to inconsistent and unreliable readings from one replication of the data loggers installed on the weirs recording runoff, only one replication of the 2003 measurements was used for this paper. Thus, runoff values provided in Table 3 should be considered estimates of the differences between the treatments. Both sprinkler heights produced runoff in 2003 as the cooperating farmer often applied irrigation at a rate greater than the soil intake capacity. Runoff was greater with in-canopy irrigation than above canopy for the conventional cultivation and basin tillage treatments (Table 3). Changes in soil moisture between sprinkler placement treatments closely agreed with runoff results collected for each placement. Greater amounts of runoff between sprinkler packages were offset by greater soil moisture loss. Runoff amounts were less for basin tillage as compared to cultivation. The reduction in runoff was due to the increase in surface storage created by the implanted basins. Although not measured, no or little runoff or signs of runoff was observed in the inter-row ripping tillage plots.

Only two significant runoff events due to irrigation, 1.1 and 0.89 inches of runoff, were recorded in 2004. This was due to management changes made by the producer. Irrigation depths in 2003 were 1.5 to 2 inches per application. In 2004, application amounts were reduced to 0.7 inches per application. This reduction in application depth reduced runoff in all but two irrigations where the producer applied higher amounts (at least 2 inches) per application.

CONCLUSIONS

Results from this study suggest that above canopy irrigation was more effective at increasing soil moisture and reducing runoff as compared to in-canopy irrigation. Less runoff from above canopy irrigation in 2003 resulted in more stored soil moisture and similar grain yield than in-canopy irrigation. In-season tillage such as basin tillage decreased runoff as compared to conventional cultivation. Yields between tillage treatments were not significantly different, but a trend of yield increases was observed when soil intake rates were modified by tillage.

No statistically significant yield differences were observed when irrigation sprinkler nozzles were placed above the canopy and soil moisture differences between above canopy and in-canopy placement reflected the differences in runoff. The results of this project suggest that sprinkler placement above a corn canopy would be preferable to placing sprinklers in-canopy unless significant changes in irrigation management practices occur.

References:

1995. Schneider, A. D. and Howell, T. A. Reducing sprinkler water losses. In Proc. 1995 Central Plains Irrigation Short Course & Equipment Exposition. Kansas Cooperative Extension Service, Manhattan, KS. pp. 60-63.

2000. Schneider, A. D. and Howell, T. A. Surface runoff due to LEPA and spray irrigation of a slowly permeable soil. Trans. ASAE 43(5):1089-1095.

Table 1. Average grain yields for sprinkler placement and tillage treatment (2003).

Tillage Treatment	Above Canopy Yield*	Above Canopy Moisture	In-Canopy Yield	In-Canopy Moisture
	(bu/acre)	(%)	(bu/acre)	(%)
Cultivation	187	15.2	182	17.5
Basin Tillage	188	14.5	184	18.1
Inter-row Rip	193	14.9	189	18.7
Average	189	14.9	185	18.1

*Grain yields adjusted to 15.5% grain moisture.

Table 2. Grain yields for sprinkler placement averaged across tillage treatments for 2003 and 2004.

Year	Grain Yield* Above Canopy	Grain Yield* In-Canopy	
	--------- bu/acre ---------		P>F
2003	189	185	0.33
2004	253	246	0.30
Average	221	216	0.17

*Grain yields adjusted to 15.5% grain moisture.

Table 3. Estimated runoff from July 4 to August 30, 2003 for sprinkler nozzle placement and tillage treatment in 2003. Runoff represents 15 irrigation events.

Tillage Treatment	--- Nozzle Placement --- Above Canopy	In-Canopy
	--------- Inches Runoff ---------	
Cultivation	5.8	9.3
Basin Tillage	0.0	2.0

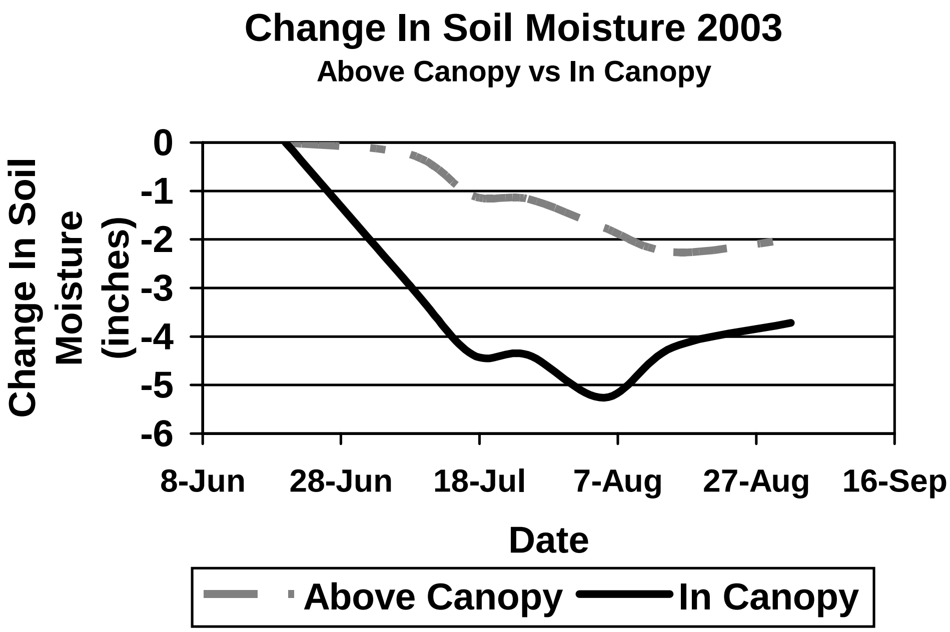

Figure 1. Change in soil moisture (from initial values) during the 2003 growing season for above canopy and in-canopy placement of sprinklers.

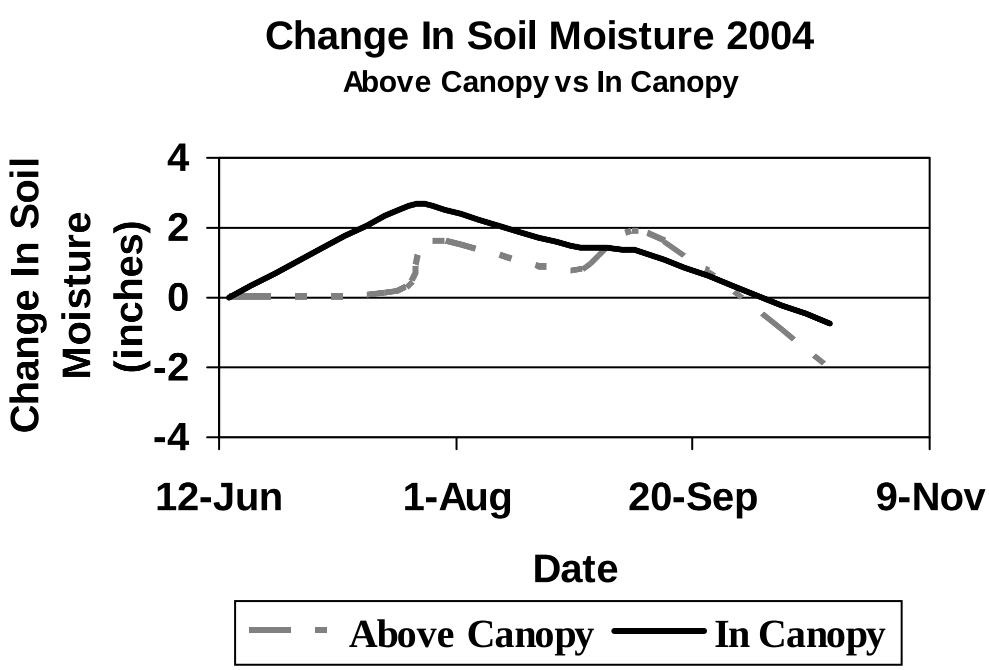

Figure 2. Change in soil moisture (from initial values) during the 2004 growing season for above canopy and in-canopy placement of sprinklers.

KEY CONSIDERATIONS FOR A SUCCESSFUL SUBSURFACE DRIP IRRIGATION (SDI) SYSTEM

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INTRODUCTION

Subsurface drip irrigation (SDI) systems are currently being used on about 15,000 acres in Kansas. Research studies at the NW Kansas Research and Extension Center of Kansas State University begin in 1989 and have indicated that these systems can be efficient, long-lived, and adaptable for irrigated corn production in western Kansas. This adaptability is likely extended to any of the deep-rooted irrigated crops grown in the region. Many producers have had successful experiences with SDI systems; however most have had to experience at least some minor technical difficulties during the adoption process. However, a few systems have been abandoned or failed after a short use period due to problems associated with either inadequate design, inadequate management or combination of both.

Both research studies and on-farm producers experience indicate SDI systems can result in high yielding crop and water-conserving production practices, but only if the systems are properly designed, installed, operated and maintained. SDI systems in the High Plains must also have long life to be economically viable when used to produce the relative low value field crops common to the region. Design and management are closely linked in a successful SDI system. A system that is not properly designed and installed, will be difficult to operate and maintain and most likely will not achieve high irrigation water application uniformity and efficiency goals. However, a correctly designed and installed SDI system will not perform well, if not properly operated and is destined for early failure without proper maintenance. This paper will review important considerations for a successful SDI system.

IMPORTANT SDI SYSTEM CONSIDERATIONS

Design considerations must account for field and soil characteristics, water quality, well capabilities, desired crops, production systems, and producer goals. It is difficult to separate design and management considerations into distinct issues as the system design should consider management restraints and goals. However, there are certain basic features that should be a part of all SDI systems, as shown in Figure 1. Omission of any of these minimum components by a designer should raise a red flag to the producer and will likely seriously undermine the ability of the producer to operate and maintain the system in an efficient manner for a long period of time. Minimum SDI system components should not be sacrificed as a design and installation cost-cutting measure. If minimum SDI components cannot be included as part of the system, serious consideration should be given to an alternative type of irrigation system or remaining as a dryland production system.

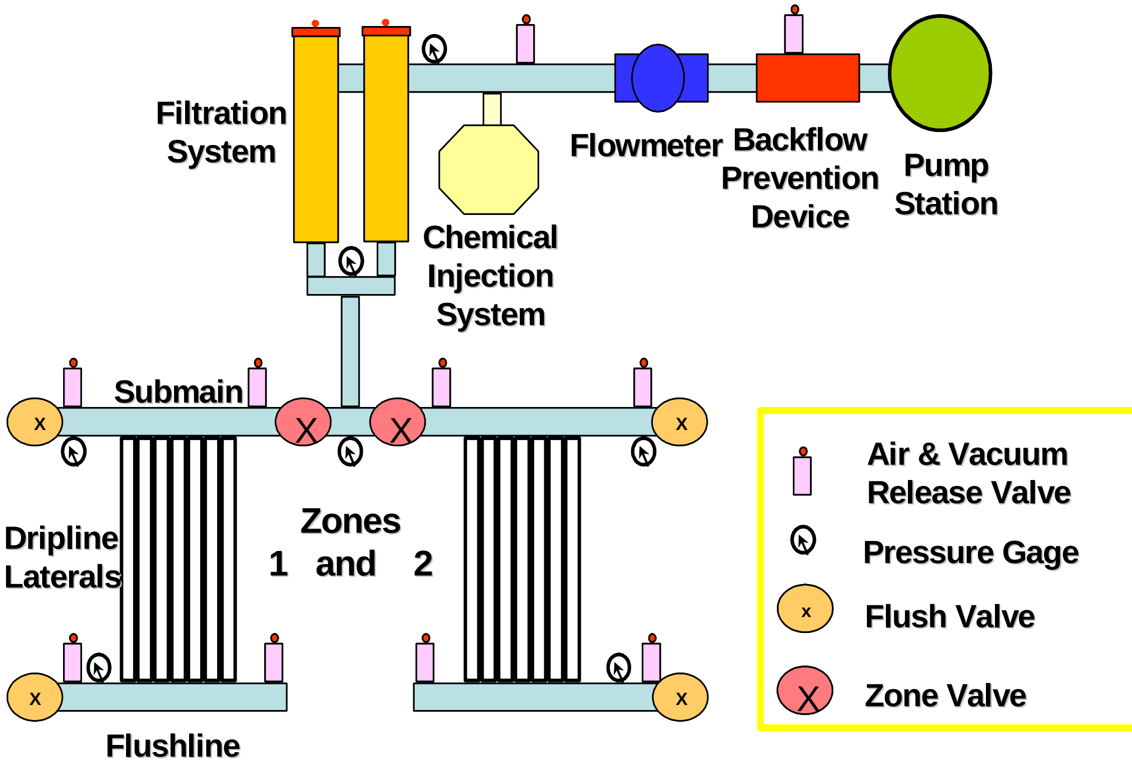

Figure 1. Schematic of Subsurface Drip Irrigation (SDI) System. (Components are not to scale) K-State Research and Extension Bulletin MF-2576, Subsurface Drip Irrigation (SDI) Component: Minimum Requirements

DISTRIBUTION COMPONENTS

The water distribution components of an SDI system are the pumping station, the main, submains and dripline laterals. The size requirements for the mains and submains would be similar to the needs for underground service pipe to center pivots or main pipelines for surface flood systems. Size is determined by the flow rate and acceptable friction loss within the pipe. In general, the flow rate and acceptable friction loss determines the size (diameter) for a given dripline lateral length. Another factor is the land slope. Theoretically, but totally unwise, a drip system could be only a combination of pumping plant, distribution pipelines and dripline laterals. However, as an underground system, there would be no method to monitor system performance and the system would not have any protection from clogging. Clogging of dripline emitters is the primary reason for SDI system failure.

MANAGEMENT COMPONENTS

The remaining components outlined in Figure 1, are primarily components that allow the producers to protect the SDI system, monitor its performance, and if desired, provide additional nutrients or chemicals for crop production. The backflow preventive device is a requirement to protect the source water from accidental contamination should a backflow occur.

The flow meter and pressure gauges are essentially the operational feedback cues to the manager. In SDI systems, all water application is underground. In most properly installed and operated systems, no surface wetting occurs during irrigation, so no visual cues are available to the manager concerning the system operating characteristics. The pressure gauges at the control valve at each zone, allows the proper entry pressure to dripline laterals to be set. Decreasing flow and/or increasing pressure can indicate clogging is occurring. Increasing flow with decreasing pressure can indicate a major line leak. The pressure gauges at the distal ends of the dripline laterals are especially important in establishing the baseline performance characteristics of the SDI system.

The heart of the protection system for the driplines is the filtration system. The type of filtration system needed will depend on the quality characteristics of the irrigation water. In general, clogging hazards are classified as physical, biological or chemical. The Figure 1 illustration of the filtration system depicts a pair of screen filters. In some cases, the filtration system may be a combination of components. For example, a well that produces a lot of sand may have a sand separator in advance of the main filter. Sand particles in the water would represent a physical clogging hazard. Other types of filters used are sand media and disc filters.

Biological hazards are living organisms or life by-products that can clog emitters. Surface water supplies may require several layers of screen barriers at the intake site to remove large debris and organic matter. Another type of filter is a sand media filter, which is a large tank of specially-graded sand and is well-suited for surface water sources. Wells that produce high iron content water, can also be vulnerable to biological clogging hazards, such as when iron bacteria have infested a well. Control of bacterial growths generally requires water treatment, in addition to filtration.

Chemical clogging hazards are associated with the chemical composition or quality of the irrigation water. As water is pulled from a well and introduced to the distribution system, chemical reactions can occur due to changes in temperature, pressure, air exposure, or the introduction of other materials into the water stream. If precipitants form, they can clog the emitters.

The chemical injection system can either be a part of the filtration system or could be used as part of the crop production management plan to allow the injection of nutrients or chemicals to enhance plant growth or yield.

The injection system in Figure 1 is depicted as a single injection point, located upstream of the main filter. In many cases, there might be two injection systems. In other cases, there may be a need for an injection point downstream from the filter location.

The injection system, when it is a part of the protection system for the SDI system, can be used to inject a variety of materials to accomplish various goals. The most commonly injected material is chlorine, which helps to disinfect the system and minimizes the risk of clogging associated with biological organisms. Acid injection can also be injected to affect the chemical characteristic of the irrigation water. For example, high pH water may have a high clogging hazard due to a mineral dropping out of solution in the dripline after the filter. The addition of a small amount of acid to lower the pH to slightly acid might prevent this hazard from occurring.

PRODUCER RESPONSIBILITIES

As with most investments, the decision as to whether the investment would be sound lies with the investor. Good judgments generally require a good understanding of the fundamentals of the particular opportunity and/or the recommendations from a trusted and proven expert. While the microirrigation (drip) industry dates back over 40 years now and its application in Kansas as SDI has been researched since 1989, a network of industry support is still in the early development phase in the High Plains region. Individuals considering SDI should spend time to determine if SDI is a viable systems option for their situation. They might ask themselves:

What things should I consider before I purchase a SDI system?

1. Educate yourself before contacting a service provider or salesperson by
   a. Seeking out university and other educational resources. Good places to start are the K-State SDI website at www.oznet.ksu.edu/sdi and the Microirrigation forum at www.microirrigationforum.com. Read the literature or websites of companies as well.
   b. Review minimum recommended design components as recommended by K-State. http://www.oznet.ksu.edu/sdi/Reports/2003/mf2576.pdf
   c. Visit other producer sites that have installed and used SDI. Most current producers are willing to show them to others.

2. Interview at least two companies.
   a. Ask them for references, credentials (training and experience) and sites (including the names of contacts or references) of other completed systems.
   b. Ask questions about design and operation details. Pay particular attention if the minimum SDI system components are not met. If not, ask why? System longevity is a critical factor for economical use of SDI.
   c. Ask companies to clearly define their role and responsibility in designing, installing and servicing the system. Determine what guarantees are provided.

3. Obtain an independent review of the design by an individual that is not associated with sales. This adds cost but should be minor compared to the total cost of a large SDI system.

CONCLUSIONS

SDI can be a viable irrigation system option, but should be carefully considered by producers before any financial investment is made.

OTHER AVAILABLE INFORMATION

The above discussion is a very brief summary from materials available through K-State. The SDI related bulletins and irrigation related websites are listed below.

MF-2361 *Filtration and Maintenance Considerations for Subsurface Drip Irrigation (SDI) Systems*
http://www.oznet.ksu.edu/sdi/Reports/2003/mf2361.pdf

MF-2576 *Subsurface Drip Irrigation (SDI) Components: Minimum Requirements* *http://www.oznet.ksu.edu/sdi/Reports/2003/mf2576.pdf*

MF-2578 *Design Considerations for Subsurface Drip Irrigation* *http://www.oznet.ksu.edu/sdi/Reports/2003/mf2578.pdf*

MF-2590 *Management Consideration for Operating a Subsurface Drip Irrigation System* *http://www.oznet.ksu.edu/sdi/Reports/2003/MF2590.pdf*

MF-2575 *Water Quality Assessment Guidelines for Subsurface Drip Irrigation* *http://www.oznet.ksu.edu/sdi/Reports/2003/mf2575.pdf*

MF 2589 *Shock Chlorination Treatment for Irrigation Wells* *http://www.oznet.ksu.edu/sdi/Reports/2003/mf2589.pdf*

Related K-State Research and Extension Irrigation Websites:

Subsurface Drip Irrigation
www.oznet.ksu.edu/sdi

General Irrigation
www.oznet.ksu.edu/irrigate

Mobile Irrigation Lab
www.oznet.ksu.edu/mil

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It is also available at
http://www.oznet.ksu.edu/irrigate/OOW/P05/Rogers.pdf

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SUBSURFACE DRIP IRRIGATION IN COLORADO

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INTRODUCTION

Drip irrigation is becoming increasingly popular in several irrigated production areas in Colorado. As of 2004, there were approximately 2,000 acres devoted to drip irrigation, most of that being permanent systems where the drip tape is buried 6-8 inches below the soil surface. Approximately 90% of the drip-irrigated acreage is being used to grow high-value vegetable crops including cantaloupe, watermelon and onions. This paper will review some of the pros and cons associated with drip irrigation practices in Colorado, as well as issues that effect its future development.

Reasons for Conversion to Drip

In Colorado=s Arkansas Valley, subsurface drip irrigation began to be adopted by commercial growers of cantaloupe in the early 1990's. The primary reason for converting from furrow to drip irrigation was not water savings, but rather improved yield and quality. In most cases, drip irrigation was used in conjunction with plastic mulch. This plasticulture-based production system dramatically improved yield and quality and accelerated crop development thus giving growers access to more lucrative markets. When cantaloupe were cultivated using furrow irrigation with no mulching, cantaloupe yields averaged about 300-400 boxes (12-16,000 lbs) per acre (Colorado Agricultural Statistics,1996). Drip irrigation in combination with plastic mulch nearly doubled that figure for most growers and was even higher under experimental conditions (Table 1). Drip irrigation also made the use of row covers more practical which further advanced the earliness of the crop.

Plasticulture, with drip irrigation as the most critical component, made the production of other vegetables like onions, peppers, and tomatoes more practical. Another notable example of a drip-irrigated specialty crop is seedless watermelon. Seedless watermelons are relatively difficult to grow and seed is extremely expensive. As a result, most seedless watermelons are established as greenhouse-grown transplants. Without drip and plastic mulch, these transplants would have an extremely high mortality rate. Overall, seedless watermelons grown with plasticulture can attain outstanding yields (Table 2).

Table 1: Yield and earliness of Earligold (Hollar Seeds), Gold Rush, and Nitro (Harris Moran) cantaloupe grown with different plasticulture combinations including drip.

Variety and Seeding or Transplanting Date	Row Cover	First Harvest	Average Fruit Size (lbs)	Market. Yield (lbs/acre)
Earligold Transplanted April 23	perforated	July 1	2.97	34,122
Gold Rush Transplanted April 23	perforated	July 5	3.07	42,608
Nitro Transplanted April 23	perforated	July 4	4.32	43,237
Earligold Seeded April 19	perforated	July 8	3.12	44,141
Earligold Transplanted May 6	none	July 8	3.53	55,837
Gold Rush Transplanted May 6	none	July 16	2.92	51,901
Nitro Transplanted May 6	none	July 11	4.43	57,241
Earligold Seeded April 19	none	July 13	3.30	51,062
LSD (0.05)=			0.52	13,155

Table 2. Marketable yield, average fruit weight, and percent stand of seedless watermelon seeded or transplanted into plastic mulches and irrigated via drip.

Establishment Method	Mulch Color	% Stand	Total Average Fruit Weight (lbs)	Total Mkt Yield (lbs/acre)
Seed	Black	50	12.5	34,321
Transplant	Black	100	13.5	51,201
Seed	Green	57	13.0	44,512
Transplant	Green	100	13.0	58,796
Seed	Clear	59	14.1	52,252
Transplant	Clear	100	12.9	55,076
lsd (.05)			1.9	16,431

As drought conditions persisted in Colorado during the 2001-2003 seasons, even more growers adopted drip irrigation. This time the driving forces were not only improved production, but water savings as well. Some of the most dramatic water savings were realized when growing onions. Onions have a extremely shallow root system, with the majority of the roots located in the top 9 inches of soil. Under furrow-irrigated conditions, a typical onion crop could require 14 or more irrigations during the course of the season with a total water application of 7 acre-ft/acre. The vast majority of the total application amount is lost to evaporation, run-off at the end of the field, and deep percolation. In contrast, drip-irrigation application rates have measured about 1.3 acre-ft/acre.

Barriers to Conversion to Drip

Although subsurface drip irrigation has shown tremendous potential in Colorado, there remain sizeable hurdles for wider-scale adoption. The first of these barriers is cost. Most of the drip irrigation systems installed in Colorado cost in the range of $800- $1300 per acre. This huge investment is a hindrance to most growers, particularly those that do not grow high value crops. Although some governmental assistance has been available, it is unlikely that growers of agronomic crops will install drip systems until a higher level of assistance can be offered. Another sizable economic challenge is the need for specialized equipment for installation and tillage.

An additional barrier is the lack of a constant and reliable water supply. Depending on the water right priority, waters originating from surface (river) flows may not be steady and constant. In times of low river flows, some delivery canals may not have access to water for weeks. This characteristic greatly diminishes the yield increase potential attributed to drip irrigation. Well water would be another potential option in Colorado; however, since the Kansas vs. Colorado conflict, well pumping has been greatly curtailed in the Arkansas River Basin and is following suit in other basins.

Future Concerns and Considerations

One of the greatest concerns pertaining to drip irrigation is the ability to secure a constant and reliable water source. Within the constraints of existing Colorado water laws, water saving methods of irrigation like drip are not justly compensated. Given the costly and contentious nature of altering existing water laws, it may prove extremely challenging to foster the future development of drip irrigation in the state.

In some parts of the state particularly the Arkansas Valley, water quality is a concern. The Arkansas River in southeast Colorado is one of the most saline rivers in the United States. Average salinity levels increase from 300 ppm total dissolved solids (TDS) near Pueblo to over 4,000 ppm TDS near the Colorado-Kansas border. More than 200,000 acres along the river are irrigated with Class C4 water, the highest classification for salinity hazard. Most surface waters also contain significant amounts of sediment. Although they lack sediment, ground waters originating from shallow wells are typically even more saline than surface water. It is not clear, if and how salts will accumulate in soils irrigated by drip. Costly maintenance procedures may be needed to ensure that drip systems function properly under poor water quality conditions.

Yet another consideration for Colorado growers is the ability to design a drip system that is able to accommodate a wide variety of crops. Most agronomic crops in the state are produced on a 30 inch row spacing making them amenable to a design containing drip lines spaced 60 inches apart. Although some vegetable crops can be grown with this type of configuration, others, like onions, are not. Since onions are planted in multiple rows per bed and are shallow-rooted, a single drip line placed in the center of the bed at depths greater than 6 inches may not be sufficient to germinate the crop and provide adequate water to the outer rows (Figure 1). In many instances, this design constraint has forced growers to drastically limit their rotation practices and thus, opens the possibility for severe pest problems.

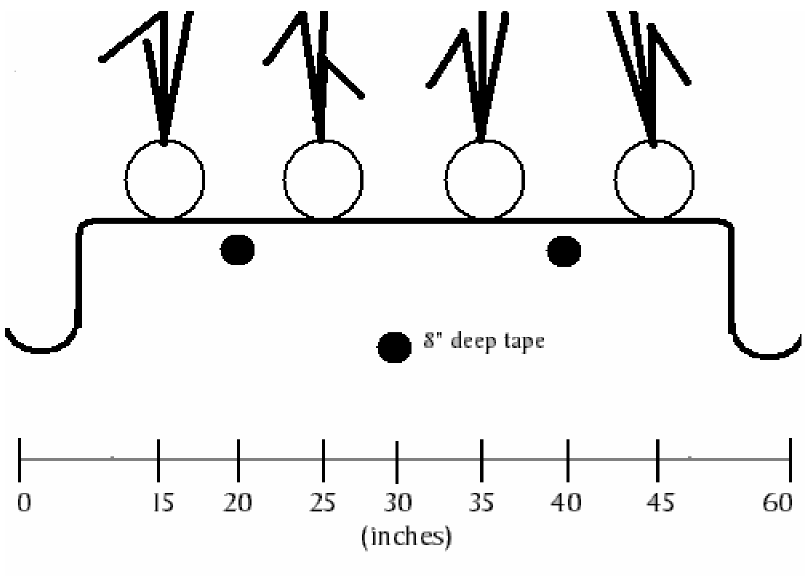

Figure 1: Comparison of drip line placement for onion production; the standard single line placed 8 inches deep in the center of the bed and the more efficient configuration of two lines placed at a shallower depth.

SUMMARY

Drip-irrigation has tremendous potential in Colorado if water law constraints can be ameliorated. As more growers adopt drip irrigation, both research and educational programs will be needed to develop and promote practices that manage the movement of salts in the soil profile and ensure sustainable and profitable cropping patterns.

COMPARISON OF SPRAY, LEPA, AND SDI FOR COTTON AND GRAIN SORGHUM IN THE TEXAS PANHANDLE [1]

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ABSTRACT

Crop responses to MESA (mid-elevation spray application), LESA (low-elevation spray applicator), LEPA, (low energy precision application), and SDI (subsurface drip irrigation) were compared for full and deficit irrigation rates in the Texas Panhandle. Crops included three seasons of grain sorghum and one season of cotton; crop responses consisted of economic yield, seasonal water use, and water use efficiency (WUE). Irrigation rates were I_0, I_{25}, I_{50}, I_{75}, and I_{100} (where the subscript denotes the percentage of full irrigation, and I_0 is dryland). Yield and WUE was greatest for SDI and least for spray at the I_{25} and I_{50} rates, and greatest for spray at the I_{100} rate. Yield and WUE trends were not consistent at the I_{75} rate. Seasonal water use was not significantly different in most cases between irrigation methods within a given irrigation rate. For cotton, the irrigation method did not influence boll maturity rates, but SDI resulted in higher fiber quality at the I_{25}, I_{50}, and I_{100} rates.

INTRODUCTION

The Southern High Plains region, which includes the Texas Panhandle, is a major producer of corn, grain sorghum, and cotton. The area centered around Lubbock is one of the largest cotton producing areas in the country, and the area from Amarillo northward has traditionally produced corn, with some of the highest yields in the nation possible with irrigation (USDA -NASS, 2004; TDA -TASS, 2004). Grain sorghum is often rotated with cotton; sorghum does not require as many heat units as cotton or as much water as corn. Greater cotton yields have been reported when rotated with grain sorghum, although gross returns were greater for continuous cotton (Bordovsky and Porter, 2004). Producers in corn producing areas are considering cotton as an alternative crop because cotton

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has a similar revenue potential as corn for about one-half the water requirement, and there has been a net increase in recent years of cotton harvested in the Northern Texas Panhandle, Northern Oklahoma, and Southwestern Kansas (USDA-NASS, 2004).

High crop yields are possible with irrigation, with increases greater than 150% over dryland to be expected (TDA-TASS, 2004). Nearly all irrigation in the Great Plains is dependent on the Ogallala aquifer, a finite water resource that is declining because withdrawals have exceeded natural recharge. The rate of decline has been reduced in recent years because irrigated land area has been reduced (either converted to dryland or abandoned), and also from conversion from gravity to more efficient center pivot sprinkler systems (Musick et al., 1990). The earliest sprinkler configurations were high-pressure impact, but these have been replaced by low-pressure spray and LEPA (low energy precision application) (Lyle and Bordovsky, 1983) since the 1980s (Musick et al., 1988). Subsurface drip irrigation (SDI) also started being adopted by cotton producers in the Trans Pecos and South Plains regions of Texas in the mid 1980s (Henggeler, 1995; 1997; Enciso et al., 2003).

Numerous studies have been conduced to document and compare the performance of various sprinkler application packages for a variety of crops and tillage configurations. These usually consisted of spray and LEPA (Schneider, 2000; Schneider and Howell, 1995; 1997; 1998; 1999; 2000). Relatively few studies also included SDI; most comparisons involving SDI were made with gravity (surface) irrigation systems (Camp, 1998; Ayars et al., 1999). A few studies did compare relative performance of spray, LEPA, and SDI for grain sorghum (Colaizzi et al., 2004a) and cotton (Segarra et al., 1999; Bordovsky and Porter, 2003; Colaizzi et al., 2004b), and reported that SDI outperformed other irrigation methods in terms of crop yield and water use efficiency at deficit irrigation rates. Nonetheless, Segarra et al. (1999) analyzed four years of cotton data at Halfway, Texas and concluded that SDI may not always provide economic returns as high as those from LEPA. But, this largely depended on system life, installation costs, pumping lift requirements, and hail damage that commonly occurs in West Texas. Some cotton producers perceive that SDI also enhances seedling emergence and plant maturity due to reduced evaporative cooling compared to LEPA or spray, which is a critical consideration in a thermally limited environment and is seldom considered in economic analyses. There is, however, limited data in direct support of this view. Soil water depletion in the root zone appears most responsible for inducing cotton earliness, regardless of the type of irrigation system used (Guinn et al., 1981; Mateos et al., 1991; Orgaz et al., 1992).

The purpose of this paper is to summarize recent research findings where crop responses to spray, LEPA, and SDI were compared directly for grain sorghum (Colaizzi et al., 2004a) and cotton (Colaizzi et al., 2004b). The research was conducted in the Texas Panhandle, where grain sorghum can be produced reliably, but the climate is marginal for cotton production.

PROCEDURE

The experiment was conducted at the USDA Conservation and Production Research Laboratory near Bushland, Texas (35° 11′ N, 102° 06′ W, 1070 m elevation MSL). Crops included grain sorghum in 2000, 2001, and 2002 and cotton in 2003 and 2004. The 2004 data have not yet been analyzed so only the results of the 2003 cotton season will be reported. We plan to continue this experiment for several more seasons of cotton. The climate is semi-arid with a high evaporative demand of about 2,600 mm per year (Class A pan evaporation) and low precipitation averaging 470 mm per year. Most of the evaporative demand and precipitation occur during the growing season (May to October) and average 1,550 mm and 320 mm, respectively. The climate is also characterized by strong regional advection from the South and Southwest, where average daily wind runs at 2 m height can exceed 460 km especially during the early part of the growing season. The soil is a Pullman clay loam (fine, mixed, thermic torrertic Paleustoll; Unger and Pringle, 1981; Taylor et al., 1963), with slow permeability due to a dense B21t layer that is 0.15 to 0.40 m below the surface and a calcic horizon that begins about 1.2 to 1.5 m below the surface.

Agronomic practices were similar to those practiced for high yield of grain sorghum and cotton in the Texas Panhandle (table 1). Grain sorghum (Sorghum bicolor (L.) Moench, cv. Pioneer [3] 84G62) was planted in the 2000, 2001, and 2002 growing seasons. In 2001, two plantings (22 May and 5 Jun) of this variety failed to emerge, so a shorter season variety (Pioneer 8966) was planted on 22 June and emerged by 2 July. It is thought that the first two plantings in 2001 failed to emerge because of excessive herbicide residual from the previous year. So in 2002, a different herbicide that was successful in earlier studies (Schneider and Howell, 1999) was used. Cotton (*Gossypium hirsutum* L., cv. Paymaster 2280 BG RR) was planted on 21 May 2003, and disked and replanted on 10 June 2003 (following severe hail damage to seedlings) at 17 plants m^{-2}. All crops were planted in east-west oriented raised beds spaced 0.76 m. Furrow dikes were installed after crop establishment to control runoff (Schneider and Howell, 2000).

The experimental design consisted of four irrigation methods, including MESA (mid-elevation spray application), LESA (low-elevation spray application), LEPA (low energy precision application), and SDI (subsurface drip irrigation), and five irrigation rates (I_0, I_{25}, I_{50}, I_{75}, and I_{100}, where the subscripts are the percentage of irrigation applied relative to the full irrigation amount). The I_{100} rate was sufficient to prevent yield-limiting soil water deficits from developing, based on crop

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[3] The mention of trade or manufacturer names is made for information only and does not imply an endorsement, recommendation, or exclusion by USDA-Agricultural Research Service.

evapotranspiration (ET_c) estimates from the North Plains ET Network (NPET, Howell et al., 1998). The different irrigation rates were used to estimate production functions, and to simulate the range of irrigation capacities typically found in the region. The I_0 rate received irrigation for emergence only and to settle and firm the furrow dikes and represents dryland production. The MESA, LESA, and LEPA irrigations were applied with a hose-fed Valmont (Valmont Irrigation, Valley, NE) Model 6000 lateral move irrigation system. Drop hoses were located over every other furrow at 1.52 m spacing. Technical details of applicators are given in table 2. The SDI consisted of Netafim (Netafim USA, Fresno, CA) Typhoon dripline that was shank injected in 1999 under alternate furrows at 0.3-m depth below the surface (before bedding). Irrigation treatment rates were controlled by varying the speed of the lateral-move system for the spray and LEPA methods, and by different emitter flow and spacing for the SDI method (table 3). All treatments were irrigated uniformly with MESA at the I_{100} rate until furrow dikes were installed to ensure crop establishment.

Soil water was measured gravimetrically near the center of each plot prior to planting and just after harvest in the 1.8-m profile in 0.3-m increments, oven dried, and converted to volumetric contents using known soil bulk densities by profile layer. During the season, soil water was measured volumetrically near the center of each plot on a weekly basis by neutron attenuation in the 2.4-m profile in 0.2-m increments according to procedures described in Evett and Steiner (1995) and Evett et al. (2003). The gravimetric samples were used to compute seasonal water use (irrigation + rainfall + change in soil water), and the neutron measurements were to verify that irrigation was sufficient so that no water deficits developed in the I_{100} treatment.

In 2000, 2001, and 2002, grain yields were measured by harvesting the full length of each plot (25 m) using a Hege (Hege Equipment, Inc., Colwick, KS) combine with a 1.52 m wide (2 row) header. Each plot sample was weighed and three subsamples were dried to determine moisture content. Grain yields reported here were converted to 14% moisture content by weight. In 2003, hand samples of bolls were collected from each plot on 19 Nov from a 10 m^2 area that was sequestered from other activity during the season. Samples were weighed, ginned, and analyzed for micronaire, strength, color grade, and uniformity at the International Textile Center, Lubbock, Texas.

Grain or lint yield, seasonal water use, and water use efficiency (WUE) were tested for differences for each irrigation method using the SAS mixed model (PROC MIXED, Littell et al., 1996). Differences of fixed effects were tested using least square means ($\alpha = 0.05$) within each irrigation rate. The WUE is defined as the ratio of economic yield (i.e., grain or lint yield, LY) to seasonal water use (WU): $WUE = LY\ WU^{-1}$. Further details of experimental design, procedures, and equipment can be found in Colaizzi et al. (2004a) for grain sorghum and Colaizzi et al. (2004b) for cotton.

RESULTS AND DISCUSSION

Rainfall was much less than the approximately 350-mm average during the 2000, 2001, and 2003 growing seasons, but slightly less than average during the 2002 growing season (table 1). A large portion of the 2002 rainfall did not occur until the grain sorghum was in its reproductive growth stages (boot, heading, and flowering), after most of the irrigations were complete, and continued into the winter. This resulted in the 2002 irrigation totals being the same as those in 2000, despite much less rainfall in 2000. The 2001 irrigation totals were less than 2000 or 2002 because a shorter season grain sorghum variety was used. Although cotton and grain sorghum have similar water requirements, the 2003 irrigation totals (cotton) were much less than other years (grain sorghum) because more water was stored in the soil profile beginning in the 2003 season from the greater rainfall in 2002, and possibly because the shortened cotton season (following replanting from hail damage) required less water (table 1).

The cotton crop reached full maturity with only 1076 °C-days (growing degree days based on a 15.6°C base temperature). This was considerably less than the 1450 °C-days thought to be required for full maturity cotton in the Southern High Plains (Peng et al., 1989), but only slightly less than that reported by Howell et al. (2004) for the 2000 and 2001 cotton seasons at our location, and was at the minimal range of growing degree days reported by Wanjura et al. (2002) for 12 years of data at Lubbock, TX. No differences in maturity rates (open harvestable bolls) were noted for any irrigation method. Differences in maturity rates appeared to vary primarily with the irrigation rate. Dryland (I_0) had the greatest soil water depletion and matured earliest, and maturity proceeded through each subsequent rate, with I_{100} maturing last. This was in agreement with Guinn et al. (1981), Mateos et al. (1991), and Orgaz et al. (1992).

Yields had greater variability by irrigation rate than by irrigation method, and increased with irrigation rate in all years except 2002 (figure 1). In some cases the increase in grain sorghum yield from I_0 (dryland) to I_{25} was nearly ten times for both relatively dry (2000) and wet (2002) years. Yield of both grain sorghum (2000, 2001, and 2002) and cotton (2003) tended to be greatest under SDI at low irrigation rates, but greatest under spray at high irrigation rates. Yield of grain sorghum under SDI was significantly greater than MESA, LESA, or LEPA at the I_{25} irrigation rate, and either numerically or significantly ($\alpha = 0.05$) greater than the other irrigation methods at the I_{50} rate in all three years. At the I_{25} and I_{50} rates, yield with LEPA was usually greater than spray but less than SDI. Cotton lint yield showed a similar trend at the I_{25} and I_{50} rates. At the I_{100} rate, yields of both grain sorghum and cotton were either significantly or numerically greatest under spray. At the I_{75} rate, this was also true for grain sorghum (except for LESA in 2002); however, lint yield of cotton under LEPA was numerically greater than SDI, and SDI was numerically greater than spray. We speculate that under low irrigation rates (i.e., I_{25} and I_{50}), more water is partitioned to transpiration and less is lost to evaporation under SDI and to a lesser extent LEPA compared to spray.

With larger irrigation rates (i.e., I_{75} and I_{100}), the yield depression observed for SDI and sometimes LEPA may have been linked to poor aeration or the leaching of nutrients below the root zone (Lamm et al., 1995). We did observe increases in volumetric soil water from about 1.8 m to 2.4 m; we conjecture that this indicates deep percolation (Colaizzi et al., 2004a). Also, the enhanced yields under spray may have been due to enhanced plant respiration while reducing transpiration during and after an irrigation event (Tolk et al., 1995).

In 2002, rainfall during the reproductive stages masked differences in grain sorghum yield among the I_{50}, I_{75}, and I_{100} rates (except LESA); the greatest grain yield of all three years occurred under I_{75} MESA at 12.2 Mg ha^{-1} (figure 1c). Grain yield for LESA in 2002 at the I_{25}, I_{50}, and I_{75} rates was less than the other methods. We are uncertain why this occurred as we observed no malfunction in irrigation or chemical application equipment. We did, however, observe a rapid and unexplained decrease in available soil water early in the season, which may have resulted in less water being available during reproductive stages later in the season. This was not observed again in 2003 for cotton lint yield.

Seasonal water use also had greater variability by irrigation rate than by irrigation method (figure 2). In most cases, there were no significant differences between irrigation methods within an irrigation rate, with the following exceptions. In 2000 at the I_{75} and I_{100} rates, and in 2001 at the I_{75} rate, water use under SDI was significantly less than under spray. In 2002, water use under SDI was significantly more than under MESA and LEPA at the I_{25} rate, and LESA and LEPA at the I_{100} rate. In 2003, SDI used significantly more water than MESA at the I_{25} rate, and LESA at the I_{50} rate. The greater seasonal water use under SDI was often linked to greater grain or lint yield. Since irrigation amounts at a given rate were the same for each irrigation method, differences in seasonal water use resulted in different amounts of soil water depletion.

Water use efficiency (WUE) generally had greater variability at smaller irrigation rates than at larger rates (figure 3). Overall trends paralleled those of crop yield, where SDI yield was greatest at small irrigation rates and spray yield was greatest at large irrigation rates. At the I_{25} rate, yield under SDI was significantly greater than that under spray and LEPA for grain sorghum and spray for cotton. At the I_{50} rate, yield under SDI was significantly greater than spray in 2000 and 2003, and MESA only in 2001. At the I_{75} rate, yield trends were not consistent, but at the I_{100} rate, yield under MESA was numerically greater than under all other methods in all years. Note that irrigation had a similar effect on WUE as it did on crop yield, where WUE was increased two to eight times from the I_0 (dryland) to the I_{25} rate.

Finally, cotton premium as determined by fiber quality parameters (micronaire, strength, length, and uniformity) were significantly greater under SDI and LEPA at the I_{25} and I_{50} rates, and numerically greater under SDI at the I_{100} rate. Further details on fiber quality and resulting premiums are given in Colaizzi et al. (2004b).

CONCLUSIONS

Yield and WUE at the I_{25} and I_{50} irrigation rates under SDI were greater than for the other irrigation methods, and yield under LEPA was usually greater than that under spray irrigation but less than that under SDI. These trends were reversed at the I_{100} rate, where yield and WUE under spray irrigation were greater than that under LEPA or SDI. Yield and WUE trends at the I_{75} rate were less consistent. Seasonal water use had greater variability by irrigation rate than by irrigation method; in most cases, there were no significant differences between irrigation methods within an irrigation rate. We speculate that under low irrigation capacities, SDI and to a lesser extent LEPA resulted in more water being partitioned to transpiration and less to evaporation. Under greater irrigation rates, SDI may have resulted in poorer soil aeration and greater nutrient leaching, while the evaporative cooling effect of spray may have enhanced plant respiration and reduced transpiration. No differences in cotton maturity were observed between irrigation methods; however, fiber quality was slightly enhanced under SDI. The lack of differences in cotton maturity may have been related to applying spray irrigation (MESA) to all plots to ensure uniform establishment. This experiment has therefore been redesigned beginning with the 2005 season to make better use of SDI to germinate the crop, which may avoid early-season evaporative cooling associated with using MESA in SDI plots.

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Table 1: Agronomic and irrigation data for three grain sorghum seasons and one cotton season.

Variable	2000	2001	2002	2003
Crop	Grain sorghum	Grain sorghum	Grain sorghum	Upland cotton
Fertilizer applied	58 kg ha^{-1} preplant N 76 kg ha^{-1} preplant P 45 kg ha^{-1} irr N (I_{100}) [a]	179 kg ha^{-1} preplant N 18 kg ha^{-1} irr N (I_{100}) [a]	160 kg ha^{-1} preplant N 57 kg ha^{-1} preplant P	31 kg ha^{-1} preplant N 107 kg ha^{-1} preplant P 48 kg ha^{-1} irr N (I_{100}) [a]
Herbicide applied	4.7 L ha^{-1} Bicep	4.7 L ha^{-1} Bicep	1.6 kg ha^{-1} Atrizine	2.3 L ha^{-1} Treflan
Insecticide applied	0.58 L ha^{-1} Lorsban	none	none	none
Gravimetric soil water samples	19-May 11-Oct	21-May 30-Oct	3-Jun 18-Nov	20-May 24-Nov
Plant variety	Pioneer 84G62	Pioneer 8966	Pioneer 84G62	Paymaster 2280 BG, RR
Plant density	30 plants m^{-2}	23 plants m^{-2}	22 plants m^{-2}	17 plants m^{-2}
Planting date	26-May	22-Jun[b]	31-May	10-Jun [c]
Harvest date	21-Sep	29-Oct	14-Nov	21-Nov
Last irrigation	28-Aug	11-Sep	8-Sep	20-Aug
I_0 total irrigation	62 mm	112 mm	62 mm	25 mm
I_{25} total irrigation	169 mm	194 mm	169 mm	71 mm
I_{50} total irrigation	275 mm	275 mm	275 mm	118 mm
I_{75} total irrigation	381 mm	356 mm	381 mm	164 mm
I_{100} total irrigation	488 mm	438 mm	488 mm	210 mm
In-season precipitation	139 mm	124 mm	317 mm	167 mm

[a] Liquid urea 32-0-0 injected into irrigation water; deficit irrigation treatments received proportionately less.
[b] Two previous plantings on 22 May 2001 and 5 Jun 2001 failed to emerge.
[c] The first planting on 21 May 2003 sustained severe hail damage on 3 June 2003.

Table 2. Sprinkler irrigation application device information.[a]

Applicator	Model[b]	Options	Applicator height from furrow surface (m)
LEPA	Super Spray head	Double ended drag sock[c]	0
LESA	Quad IV	Flat, medium grooved spray pad	0.3
MESA	Low Drift Nozzle (LDN) spray head	Single, convex, medium grooved spray pad	1.5

[a] All sprinkler components manufactured by Senninger (Senninger Irrigation, Inc., Orlando, Florida) except where noted.
[b] All devices equipped with 69 kPa pressure regulators and #17 (6.75 mm) plastic spray nozzles, giving a flow rate of 0.412 L s^{-1}.
[c] A.E. Quest and Sons, Lubbock, TX.

Table 3. Subsurface drip irrigation (SDI) dripline information.[a]

Irrigation Rate	Emitter Flow Rate (L hr^{-1})	Emitter spacing (m)	Emitter application rate (mm hr^{-1})
I_0		Smooth tubing – no emitters	
I_{25}	0.68	0.91	0.49
I_{50}	0.87	0.61	0.97
I_{75}	0.87	0.41	1.45
I_{100}	0.87	0.3	1.93

[a] All SDI dripline manufactured by Netafim (Netafim USA, Fresno, CA).

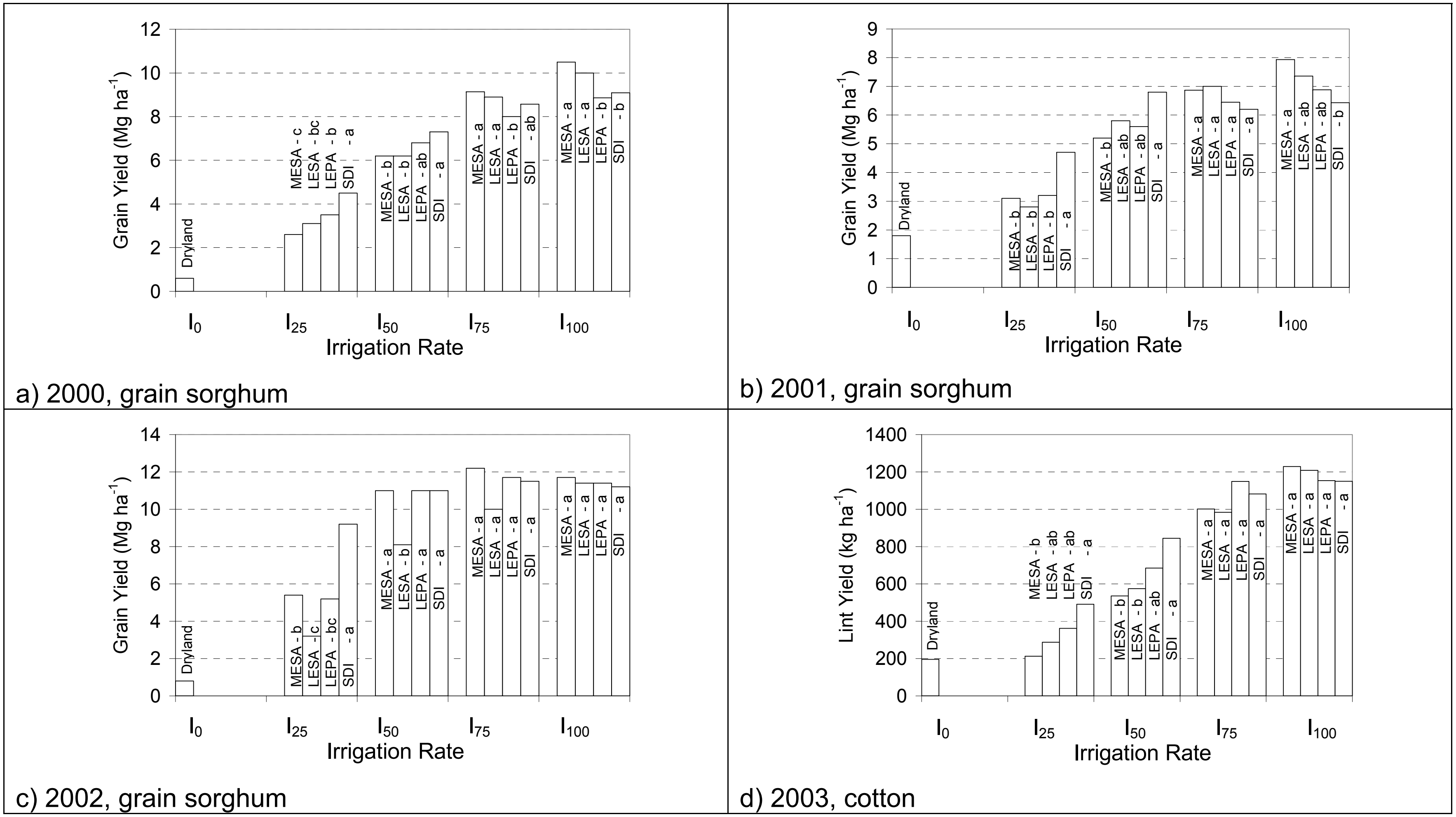

Figure 1: Economic yield for grain sorghum and cotton. Irrigation methods followed by the same letter are not significantly different (α = 0.05) within an irrigation rate.

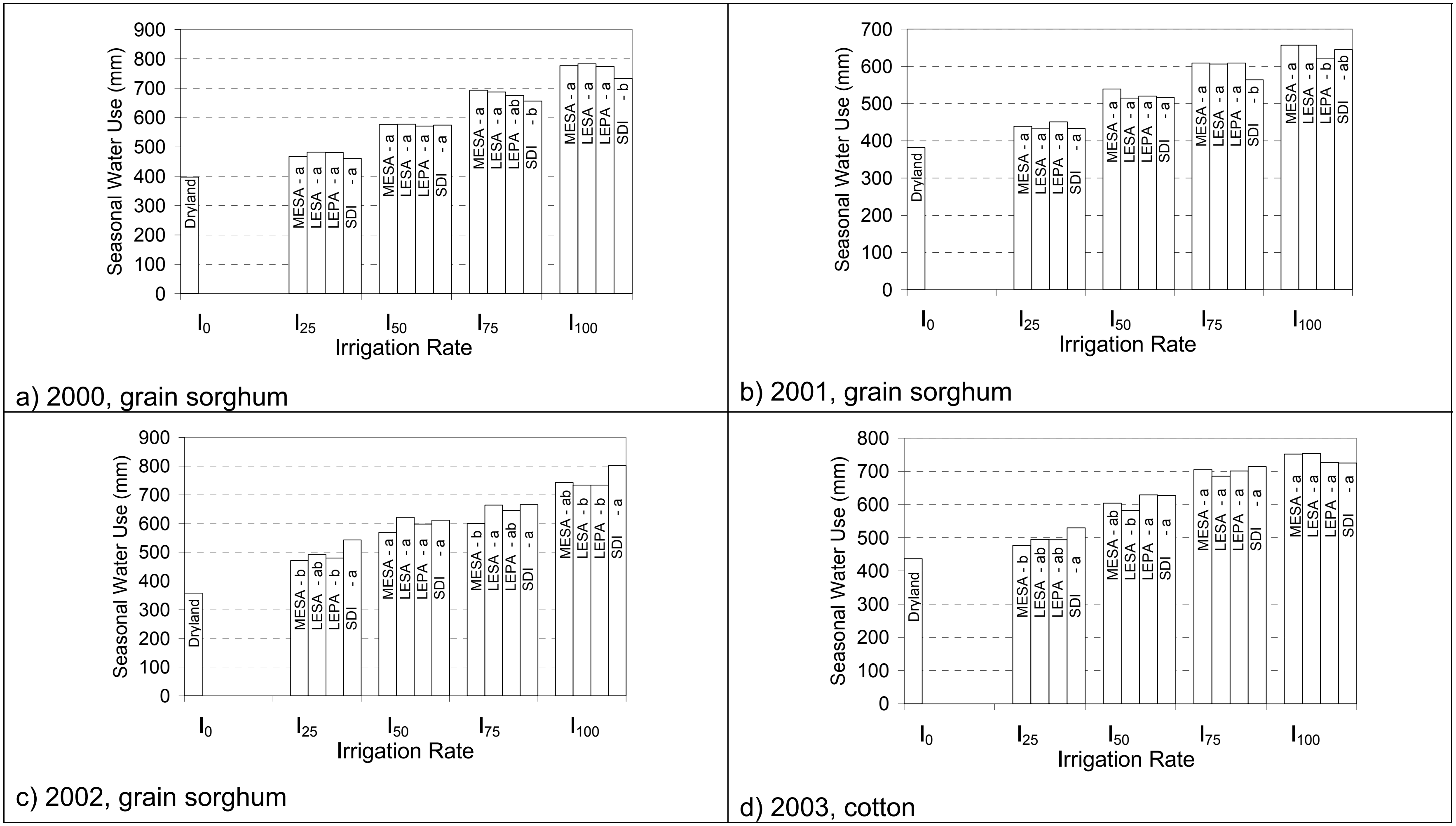

Figure 2: Seasonal water use for grain sorghum and cotton. Irrigation methods followed by the same letter are not significantly different (α = 0.05) within an irrigation rate.

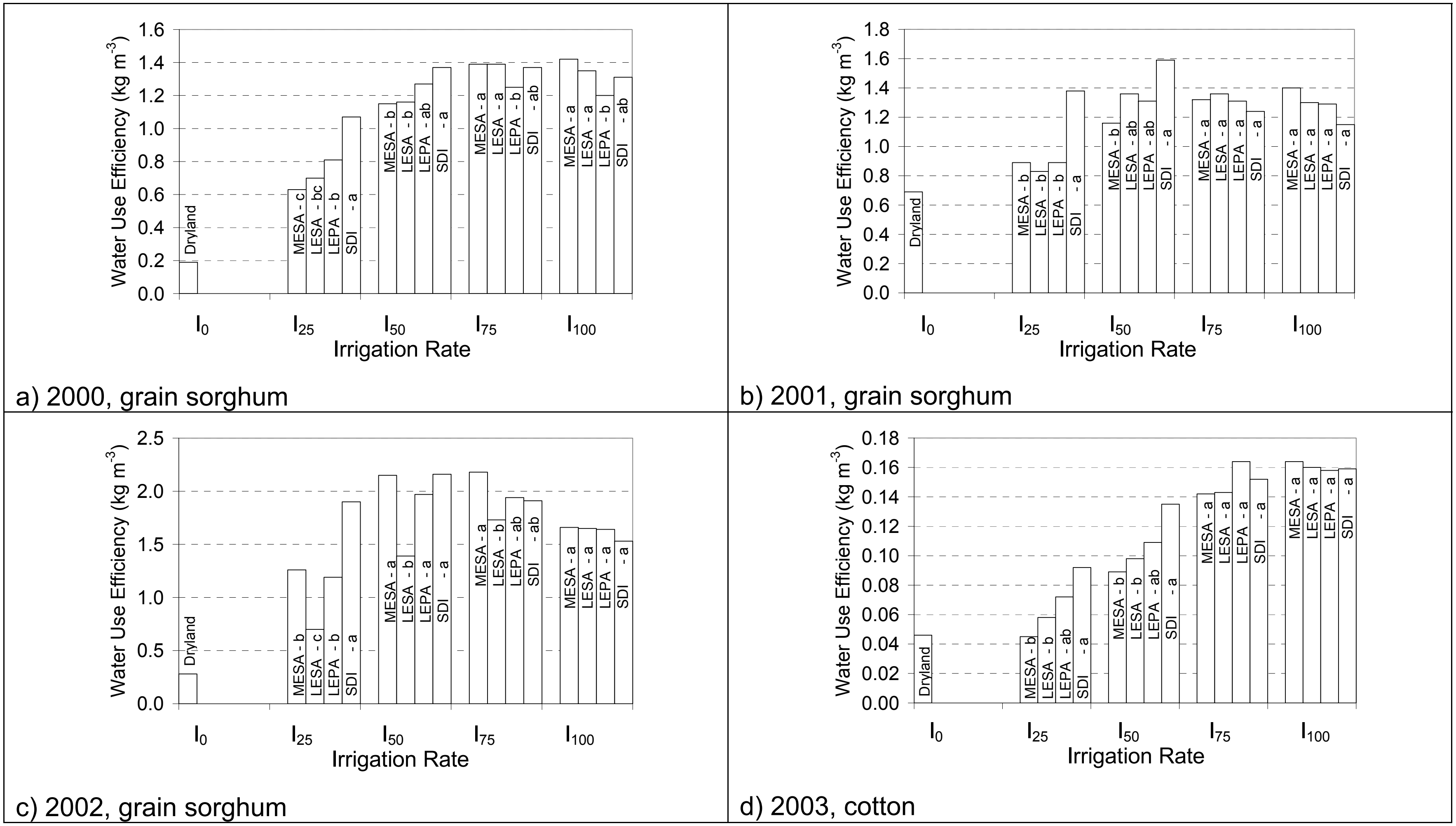

Figure 3: Water use efficiency (WUE) for grain sorghum and cotton. Irrigation methods followed by the same letter are not significantly different ($\alpha = 0.05$) within an irrigation rate.

CENTER PIVOT EVALUATION AND DESIGN

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INTRODUCTION

The Center Pivot Evaluation and Design Program (CPED) is a simulation model. It is based on the first model presented by Heermann and Hein (1968) which was verified with field data. Their simulation model required input of the sprinkler location, discharge, pattern radius and an assumed stationary pattern shape of either triangular or elliptical. The application depth versus distance along a radial line from the pivot was determined and application rates at a specified distance from the pivot were determined. The hours per revolution were input and each tower was assumed to move at a constant speed for the complete circle. Kincaid, Heermann and Kruse (1969) used the model to calculate potential runoff for different system capacities and infiltration rates. Kincaid and Heermann (1970) added the calculation of the flow resistance and verified with measured pressure distribution along the center pivot lateral. Chu and Moe (1972) studied the hydraulics of a center pivot system and developed a quick approximation for determining the pressure loss from the pivot to the outer end of the lateral as a constant (0.543) times the loss that would occur if the entire discharge flowed the total length of the lateral.

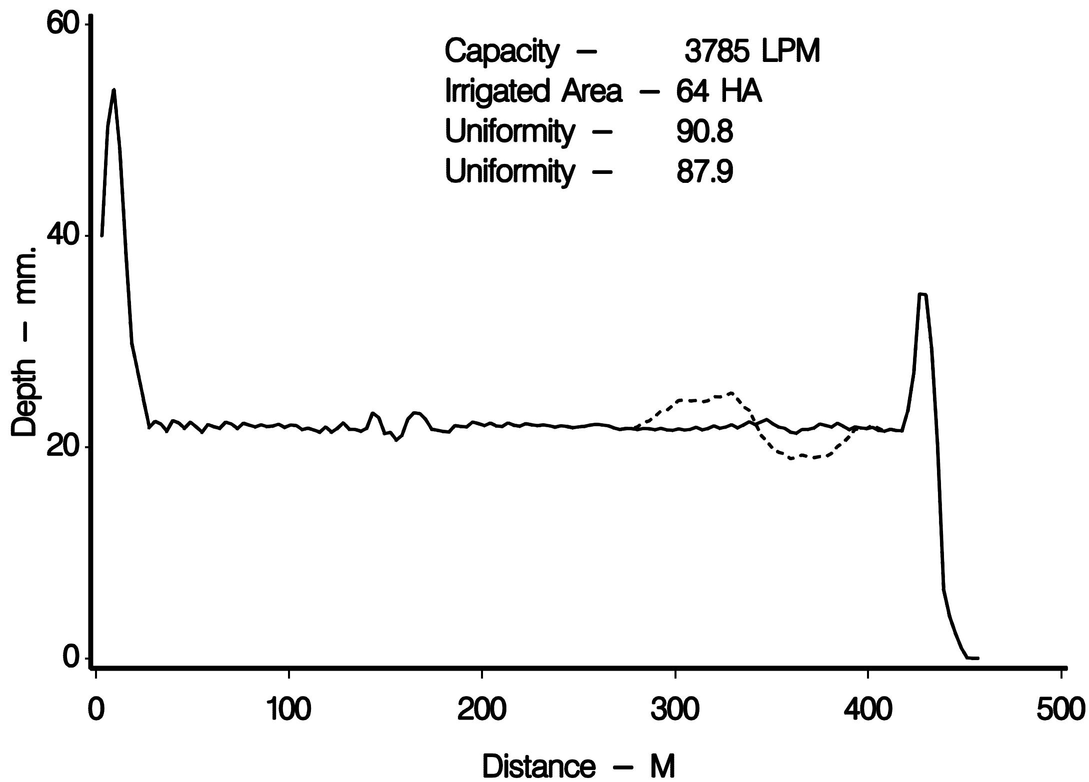
The model was adapted by Beccard and Heermann (1981) to include the effect of topographic differences in the resulting application depths along radii of the center pivot in non level fields. The model included the pump and well characteristics and calculated the hydraulic equilibrium point as the system moved to different positions on a rough terrain. The model was exercised to determine the uniformity changes when converting from high pressure to low pressure on rough terrain. Edling (1979), and James (1984) also used simulation models to study the performance of center pivot systems on variable topography and with different pressures.

The current simulation model has been expanded to include donut shaped stationary patterns that can be used to represent many of the low pressure spray heads. The start-stop of the electric motors and the speed variation in hydraulic drives can also effect the uniformity in the direction of travel (Heermann and Stahl, 1986). The input of the start-stop sequence for each tower replaces the assumption of a constant speed and the variability of application depths in the direction of travel has been simulated.

EXAMPLES OF SIMULATION EVALUATION

The uniformity of application depths can be calculated by inventorying the sprinkler head models, nozzles sizes and distance from the pivot. The pump curve and drawdown, or pivot pressure, or discharge is also needed. Figure 1 illustrates a simulation as designed and the distribution if the sprinkler heads were reversed between 2 towers made at the time of installation. The application rate and potential runoff are illustrated in Figure 2.

Figure 1. Typical center pivot as designed (CU = 90.8) and with 10 sprinkler heads incorrectly installed shown as a dashed line (CU = 87.9).



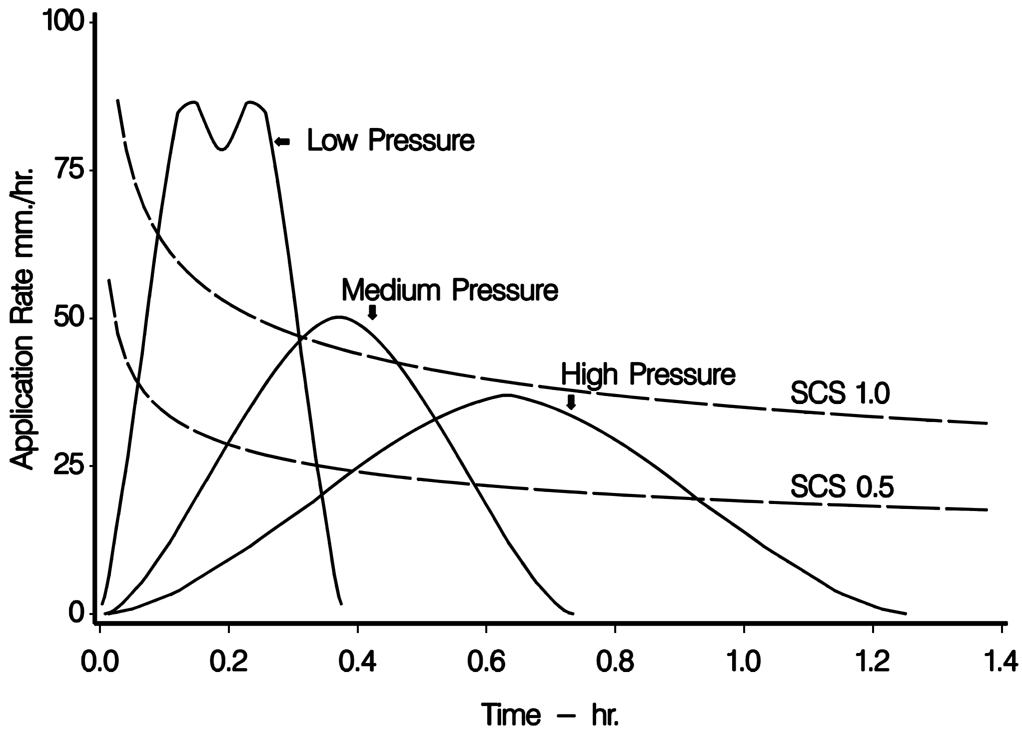


Figure 2 Example application rate curve versus 0.5 and 1.0 SCS intake curve.

EVALUATION OBJECTIVES

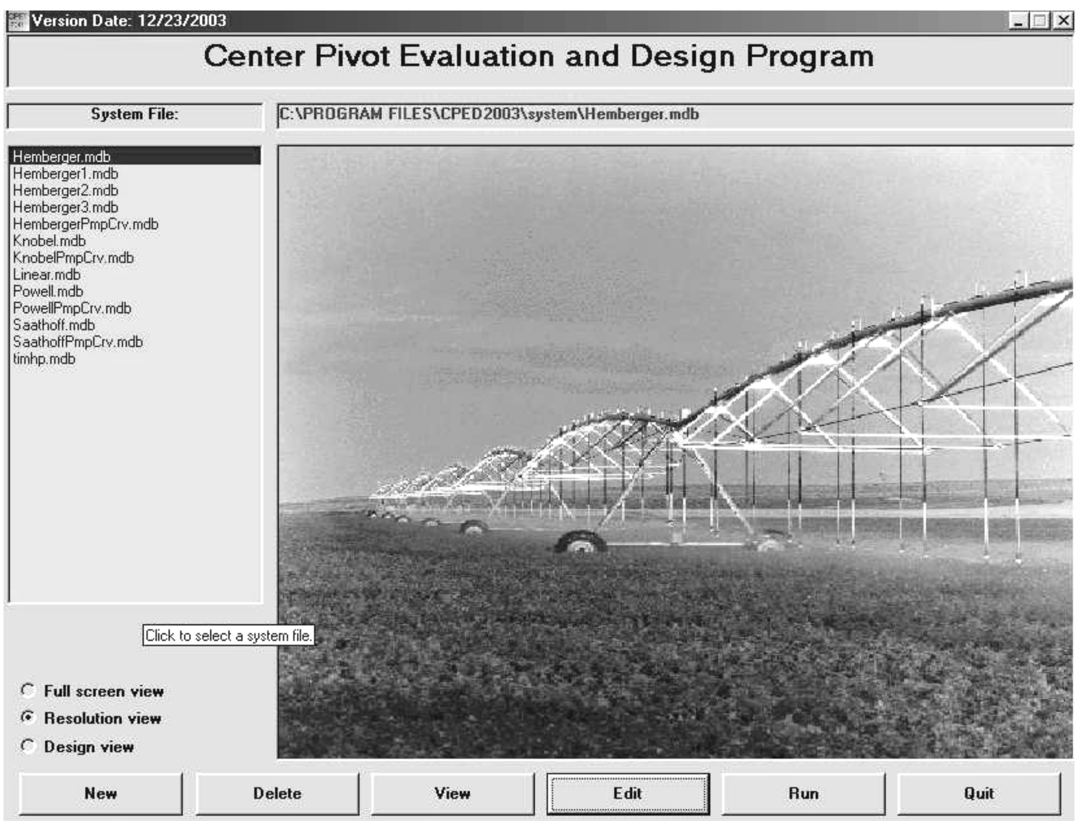
The selection or development of an evaluation standard and procedures should focus on the need for the evaluation. The USDA, Environmental Quality Incentive Program (EQIP) administered by the Natural Resource Conservation Service (NRCS) currently can provide cost sharing on the installation and upgrading of irrigation systems for improving water quality or conservation under irrigation. Center pivots are frequently the system of choice. There is a need to assure that installed systems will provide the desired improvement in irrigation performance. A similar need exists for any user of center pivot systems to assure that an installed or modified system will perform as designed. It must be recognized that the scheduling of irrigations is most important for the beneficial use of water. Efficient scheduling of irrigation systems requires knowing the amount of water applied per irrigation. The CPED program has been streamlined and simplified for use in evaluating center pivot systems for cost sharing on new and upgraded systems. The CPEDLite program is similar to the one being used in this workshop. The primary difference is the simulations are for 1 foot intervals beginning and ending at fixed distances. This assures that any simulation will provide the same results. The uniformity is output in 5% bands.

CPED PROGRAM OPERATION

The following pages will present the various windows that are presented to the user for controlling the input and operation of the program. The program illustrated is the full version of CPED. The CPEDLite program has the same look at the window level but requires less input with some of the options being fixed so that similar results will be obtained independent of the operator.

The program is available on request but the user is cautioned that there is always the possibility of program errors when different systems present conditions that have not been experienced prior to this time. The program is therefore limited in its release to minimize the problems of users that are not familiar with center pivot operation and terminology.

MAIN PROGRAM WINDOW



The options available are to **select** or create a **new** system file, **view** output from previous simulations, and **quit** the program. Once a system file is **selected** or created, the options to **run, edit, or delete** the system file are enabled. In all cases throughout the program "click" means click the left mouse button.

A system file can be **Selected** by clicking one of the systems listed in the list box labeled *System File List.* The name of the selected system file will be displayed in the label box labeled *Name of Selected System File.*
The **New** button allows the user to create a new system file. There are two ways to create a new system. The first way is to enter a name and click the OK button. You are then transferred into the Edit window that is discussed below. The second option is to create a system from an existing file. You then select the existing file; name the new system; click the OK button and you will be in the Edit window where only changes need to be entered.

The **Delete** button will delete the selected system file from the user's hard drive. The user will be asked for confirmation before deleting a system file.

The **View** button allows examining previous simulation results. The *View previous output* button will bring up the data files that have been saved from previous simulations. Selecting one of these files will plot to the screen the simulated depth versus distance data.

The *Analyze catch can data* button allows you to enter catch can data for uniformity evaluation. A simulation output data set can be input to the catch can data file and allow the uniformity analysis for different distances along the lateral. The procedure to save simulation data is presented latter with running the program.

The **Edit** button allows editing of the selected system file. More detail is below.

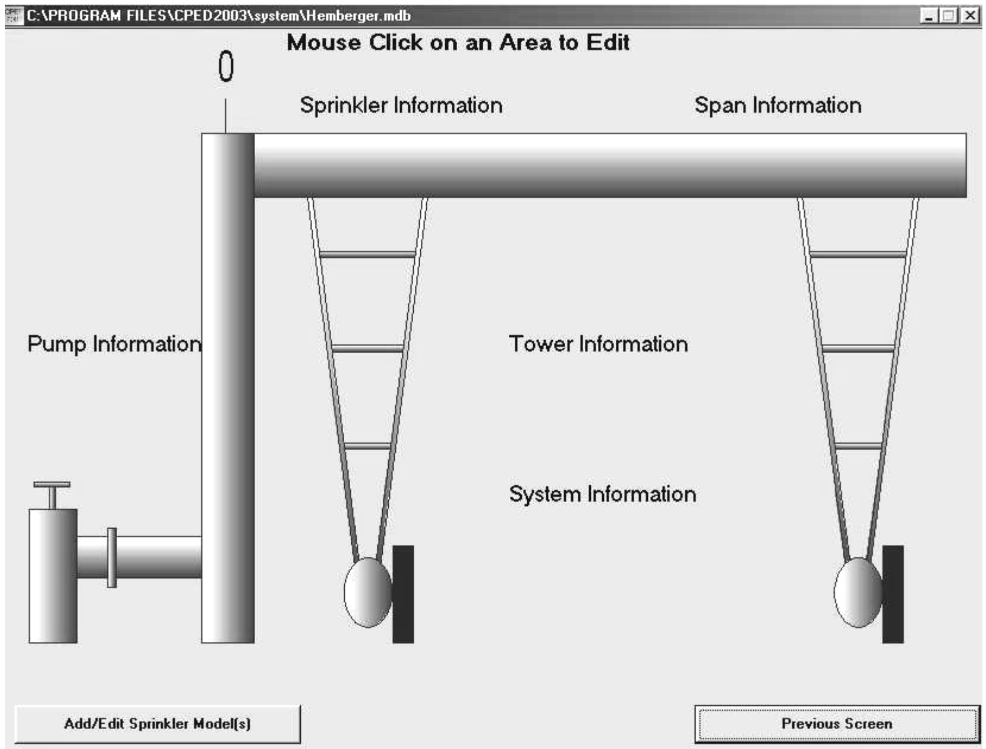
The **Run** button moves to the screen for entering the parameters to run the simulation. More detail is given below.

The **Quit** button exits the program. Pressing CTRL +Q anytime during the simulation will have the same effect.

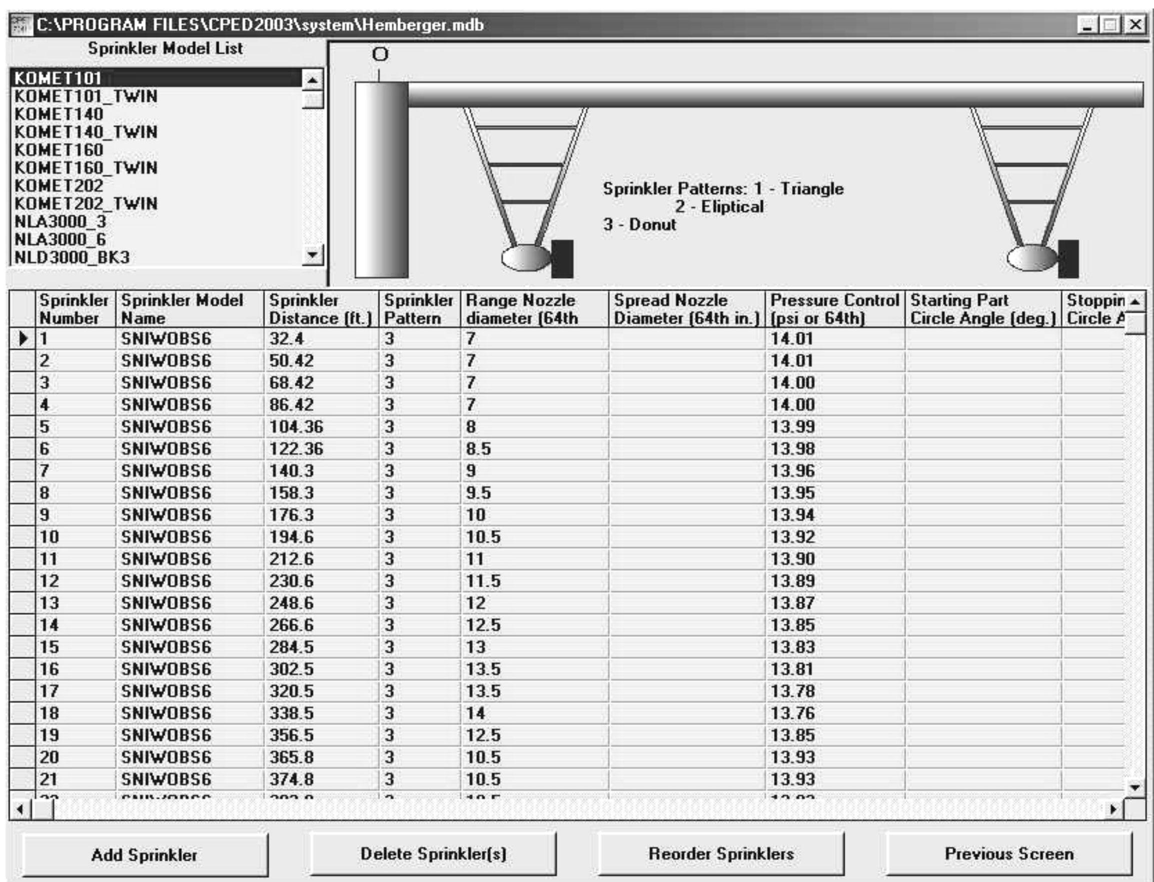
EDIT SYSTEM FILE WINDOW

The different information groups of data can be entered or edited by moving the mouse pointer over the image of the sprinkler system. The labels *Pump Information, Tower Information, Sprinkler Information, Span Information, and System Information* can be selected by clicking on the text to open its edit window.

The *Add/Edit Sprinkler Model* button opens a window for adding or editing sprinkler models. This is password protected and normally is not needed by the user. Those supporting the program will do this editing. The *Previous Window* button saves the changes and returns to the main program window.



SPRINKLER EDIT WINDOW



Sprinkler Number	Sprinkler Model Name	Sprinkler Distance (ft.)	Sprinkler Pattern	Range Nozzle diameter (64th	Spread Nozzle Diameter (64th in.)	Pressure Control (psi or 64th)	Starting Part Circle Angle (deg.)	Stoppin Circle A
1	SNIWOBS6	32.4	3	7		14.01		
2	SNIWOBS6	50.42	3	7		14.01		
3	SNIWOBS6	68.42	3	7		14.00		
4	SNIWOBS6	86.42	3	7		14.00		
5	SNIWOBS6	104.36	3	8		13.99		
6	SNIWOBS6	122.36	3	8.5		13.98		
7	SNIWOBS6	140.3	3	9		13.96		
8	SNIWOBS6	158.3	3	9.5		13.95		
9	SNIWOBS6	176.3	3	10		13.94		
10	SNIWOBS6	194.6	3	10.5		13.92		
11	SNIWOBS6	212.6	3	11		13.90		
12	SNIWOBS6	230.6	3	11.5		13.89		
13	SNIWOBS6	248.6	3	12		13.87		
14	SNIWOBS6	266.6	3	12.5		13.85		
15	SNIWOBS6	284.5	3	13		13.83		
16	SNIWOBS6	302.5	3	13.5		13.81		
17	SNIWOBS6	320.5	3	13.5		13.78		
18	SNIWOBS6	338.5	3	14		13.76		
19	SNIWOBS6	356.5	3	12.5		13.85		
20	SNIWOBS6	365.8	3	10.5		13.93		
21	SNIWOBS6	374.8	3	10.5		13.93		

A new sprinkler can be added by clicking the *Add Sprinkler* button. If no sprinklers are present by pressing the *Add Sprinkler* button a sprinkler with zero distance will default and you can begin by entering the other information for the first sprinkler. The sprinkler model is selected by clicking on the model listed in the box labeled *Sprinkler Model List*. Sprinklers can be added in any order. If one sprinkler is missed you can merely add it at any time. By clicking the *Reorder Sprinklers* button the sprinklers will be ordered from the pivot to the outer end based on their individual distances from the pivot. You do not enter the sprinkler number as this is done automatically. If sprinklers are present the information from the previous record will be used and the distance will automatically be incremented. Edit the information for the newly added sprinkler. Many systems will have the same sprinkler models and these will need no editing. If the sprinkler spacing is uniform this will also require minimal editing. Even the nozzle sizes may be the same for several sprinklers minimizing the editing required.

The nozzle size is the diameter in 1/64 inches. For example a nozzle diameter of 9.5 is equal to 9.5/64 or 19/128 inch. There are columns for a range and spread nozzle which was typical for high pressure heads. Enter the diameter for single nozzle sprinklers in the range column. The pressure control column is the outlet pressure of the pressure regulator if this is selected in the *System file screen.* When the constant orifice is the selected pressure control, the orifice size in 64^{th} inch is entered. When this column is left blank, it is an indication there is no flow control on that sprinkler even if the system has pressure regulation selected.

The start and stop angles are viewed from the pivot toward a part circle sprinkler. Check if the sprinkler starts on the right or left. Then using the pipe as the zero reference point, measure the angle back toward the pivot. Use the same technique for the stop angle. All angles are positive and between 0 and 180 degrees (Figure 3).

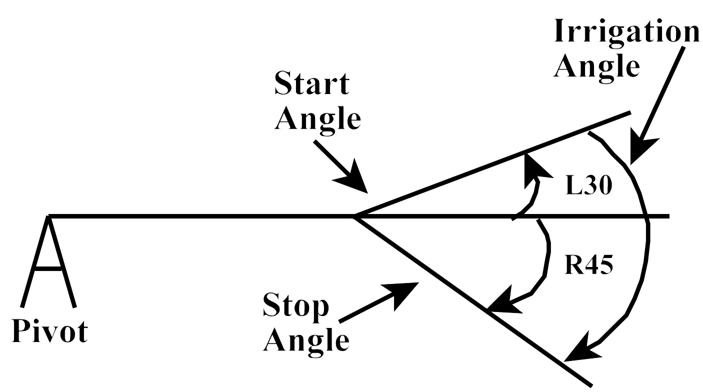


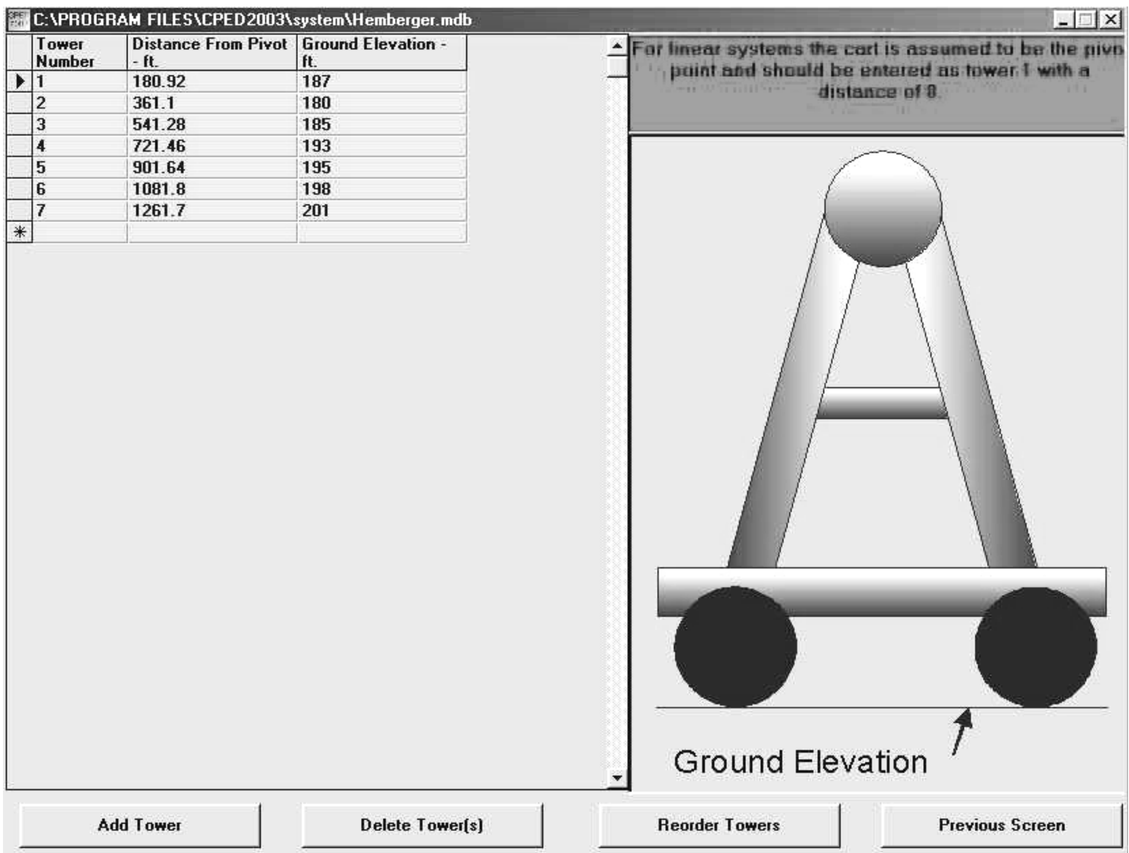
Figure 3. Part circle sprinklers angles. Angles are between 0 -180 degrees with an L or R prefix.

Alternatively you can move to the bottom row marked with an '*' and enter the new sprinkler information manually. A sprinkler can be deleted by selecting any column in the row for the sprinkler and click the *Delete* button.

The *Reorder* button will sort and number the sprinklers by sprinkler distance from the pivot.

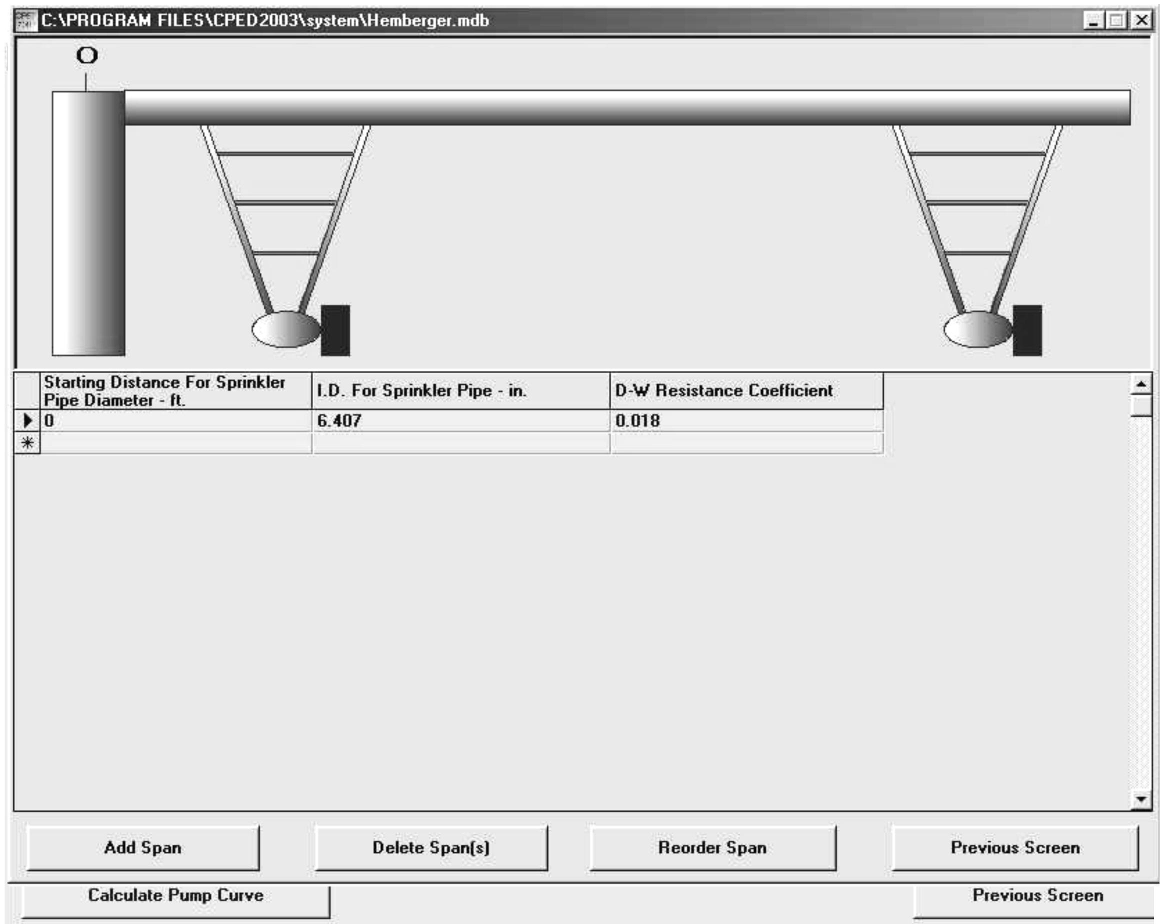
The *Previous Screen* button returns to the **Edit system file window**.

TOWER EDIT WINDOW



Towers are added by clicking on the *Add Tower* button and editing the distance from the pivot and its elevation. It is often assumed that the pivot and all towers are at an elevation of 100 feet if no field information is available. For the linear system, the first cart is assumed to be the pivot with a distance of 0. As the *Add Tower* button is clicked, the towers are added with the spacing of the previous two towers and the same elevation as the previous tower. The *Reorder Towers* will sort the towers by distance from the pivot if there happen to be entered in the wrong sequence. Select a tower and click the *Delete Tower* button if a tower needs to be deleted. The *Previous Screen* returns to the *Edit system file window.*

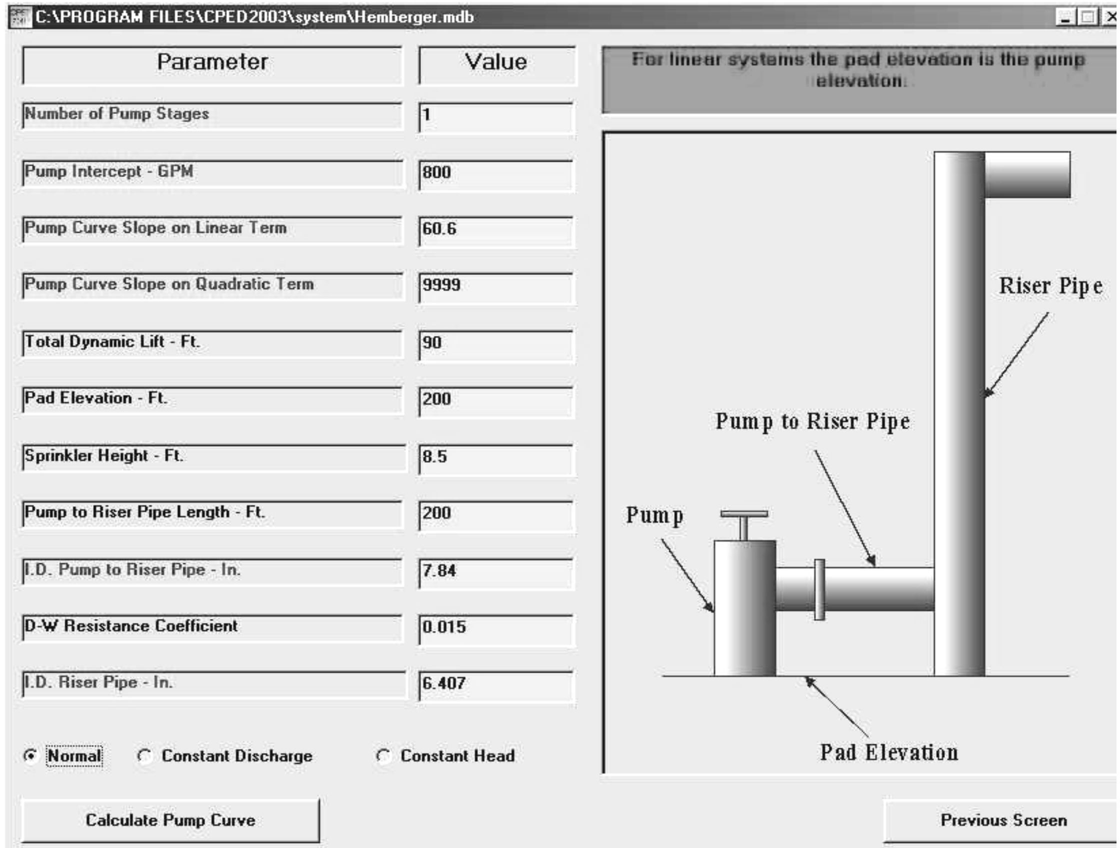
SPAN INFORMATION WINDOW



Clicking the *Add Span* button inserts a starting distance of 0 and the Pipe I.D. and the Darcy-Weisbach resistance coefficient must be entered. A typical value of the D-W coefficient is 0.xxx to 0.xxx for center pivots. Multiple pipe sizes can be added by clicking the *Add Span* button and entering the starting distance from the pivot and its resistance coefficient. The spans are assumed to go from the starting distance to the next span or end of the pivot for the last span. Spans can be deleted (*Delete Span)* and reordered (*Reorder spans)* by clicking the appropriate button. Never delete the span with starting distance of 0. The *Previous Screen* button returns to the *Edit system file window.*

PUMP INFORMATION WINDOW

The piping to the pivot, pump curve, and pivot elevation are entered in this window. If the pump curve information is not available, either a constant discharge or constant pressure can be selected.



Selecting the *Normal* option requires the quadratic equation for the pump curve. The curve of the total head vs discharge for the pump is needed to develop the regression equation that describes the pump. This relationship can be determined externally from this program or there is an option that will fit the pump curve equation with points from a pump curve or field measured data. At least 4 points that span the operating range are needed, however 8-10 will give a better fit. Problems have occurred where the operating point is beyond the pump curve data. **Use caution.** The form of the equation for the pump curve is:

$$Q = B_0 + B_1H + B_2H^2$$

where:

- Q - discharge - gpm
- H - head/stage - psi
- B_0 - intercept
- B_1 - linear slope coefficient on head
- B_2 - quadratic slope coefficient on head

The number of stages for the pump must be entered when the manufacturers pump curve is for a single stage. However, if the pump curve comes from field measurements, set the number of stages equal to one. The *Calculate Pump Curve* button can be selected for calculating the coefficients when data are available from either the manufacturers pump curve or field measured data. The paired data of discharge in gpm and head in feet can be entered and the three coefficients calculated.

The total dynamic lift in feet must also be entered. It is the elevation difference (feet) between the center pivot pad elevation and the depth to the water table including the drawdown while pumping. The pad elevation is the elevation for the center pivot at from an assumed or measured datum elevation. The sprinkler height is the distance above the pad height for the sprinklers as if they were on a level field. The inside diameter (I.D.) of the pipe size and length of pipe from the pump to the pivot and the I.D. of the riser pipe must be entered. Include the Darcy-Weisbach coefficient for both pipes.

The *Constant Head* option is where the pivot pressure (psi) is specified. This is the most stable option where the pump curve is not known. Estimate the discharge in gpm and set the number of stages equal to one. The estimate discharge is only to shorten the calculation time and the actual value is not critical.

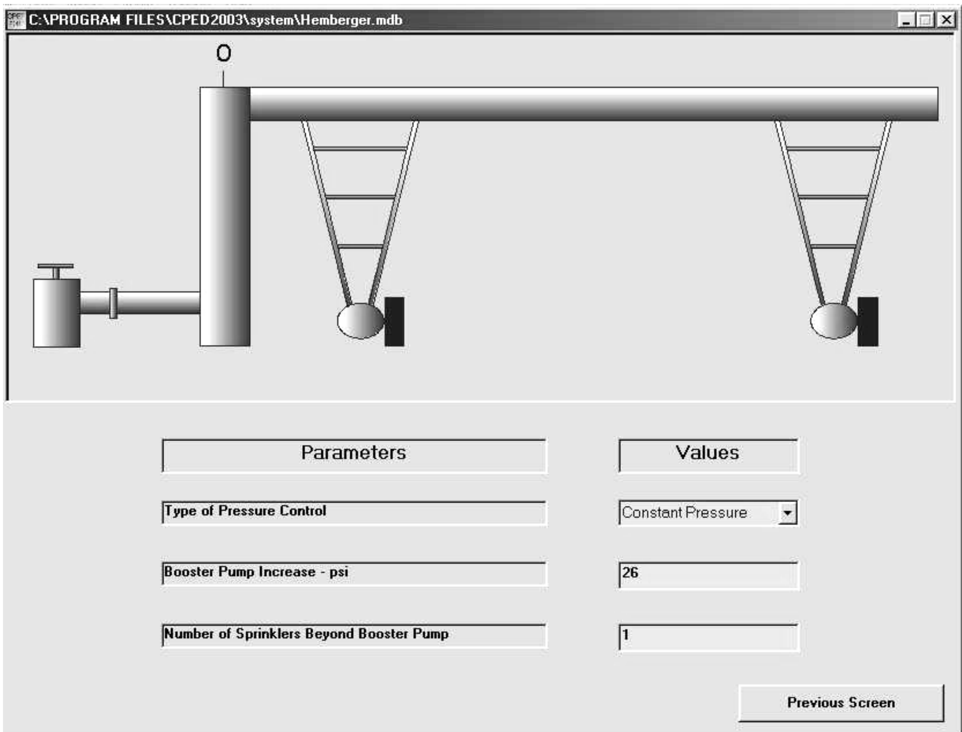
The *Constant Discharge* in gpm can also be specified. The potential problem with constant discharge is when all sprinklers are regulated. If the discharge does not match the calculated discharge with the regulated pressure an error will occur when attempting to have the calculated discharge on the system match that specified. Again set the number of stages equal to one.

The constant head and constant discharge does not require pump to riser pipe and riser pipe sizes or resistance coefficient since the pressure or discharge is assumed to be at the pivot and no head loss is calculated for these sections. The *Previous Screen* button returns to the *Edit system file window.*

SYSTEM INFORMATION SCREEN

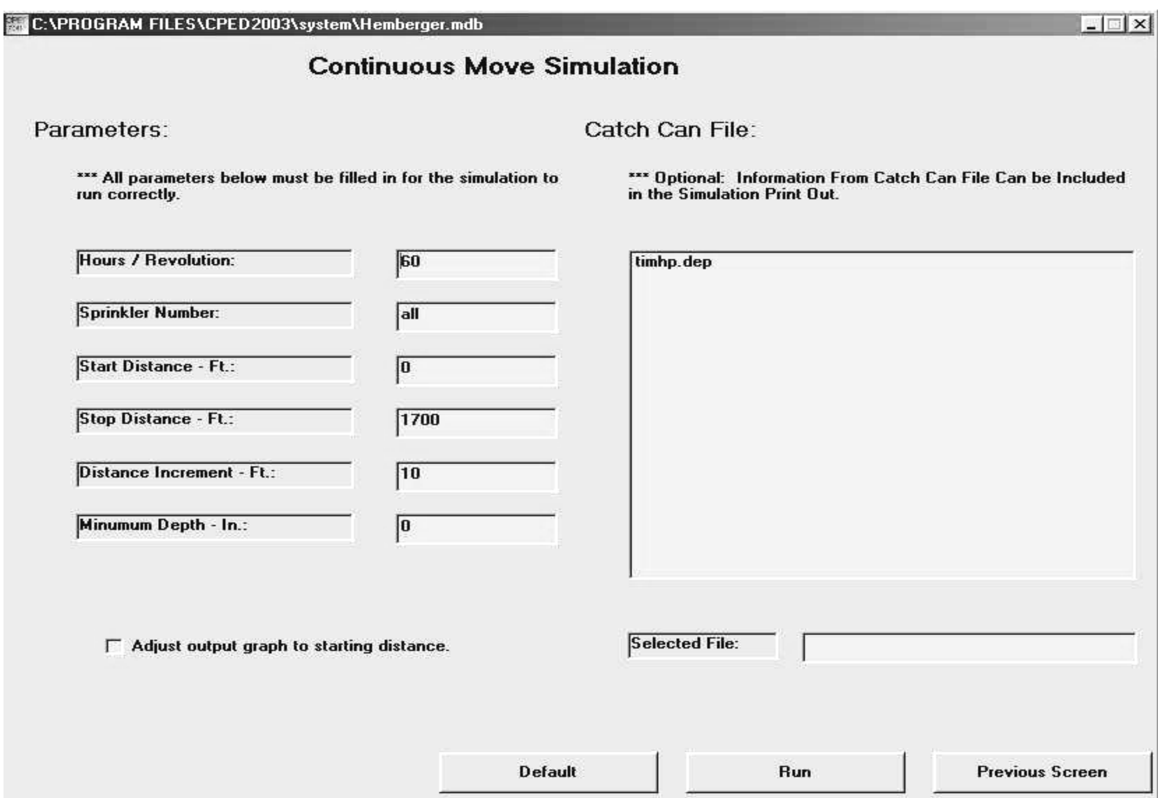
Three options for the *Type of Pressure Control* can be select from the drop down box. They are none, pressure regulated, or constant orifice. Systems with booster pumps for the big gun at the end of a center pivot system are simply estimated with a pressure increase in psi just prior to the big gun or guns. The number of sprinklers beyond the booster pump is specified. The actual pressure is dependent on the center pivot system and the inlet pressure, discharge or pump curve.

The *Previous Screen* button returns the *Edit system file window*.



C:\PROGRAM FILES\CPED2003\system\Hemberger.mdb
0
Parameters
Values
Type of Pressure Control
Constant Pressure
Booster Pump Increase - psi
26
Number of Sprinklers Beyond Booster Pump
1
Previous Screen

RUN WINDOW



C:\PROGRAM FILES\CPED2003\system\Hemberger.mdb
Continuous Move Simulation
Parameters:
*** All parameters below must be filled in for the simulation to run correctly.
Hours / Revolution:
60
Sprinkler Number:
all
Start Distance - Ft.:
0
Stop Distance - Ft.:
1700
Distance Increment - Ft.:
10
Minumum Depth - In.:
0
Adjust output graph to starting distance.
Catch Can File:
*** Optional: Information From Catch Can File Can be Included in the Simulation Print Out.
timhp.dep
Selected File:
Default
Run
Previous Screen

This is the screen that you will enter when you click *RUN* and all of the system files with the necessary data have been entered. Minimal input is required on this screen before the simulation is run. The *Default* button will restore the default values that were used on the previous simulation run for this system. The hours/revolution are entered to obtain the depth for this condition. Normally the sprinkler number is set to “all” for including all the sprinklers to be simulated. However, you can select one sprinkler by entering its number to see the contribution to the depths from the specified sprinkler.

The start, stop distances and distance increment specifies the location for simulation depths. For example you can start at 10 feet and go to 500 feet with 5 foot increments. The minimum depth specifies that only locations with depths greater than that will be included in the uniformity calculations. This is often desirable when not including the small depths at the outer boundary where there is not sufficient overlap with other sprinklers. The CPEDLite program fixes these four parameters and only the speed in hours/revolution can be changed.

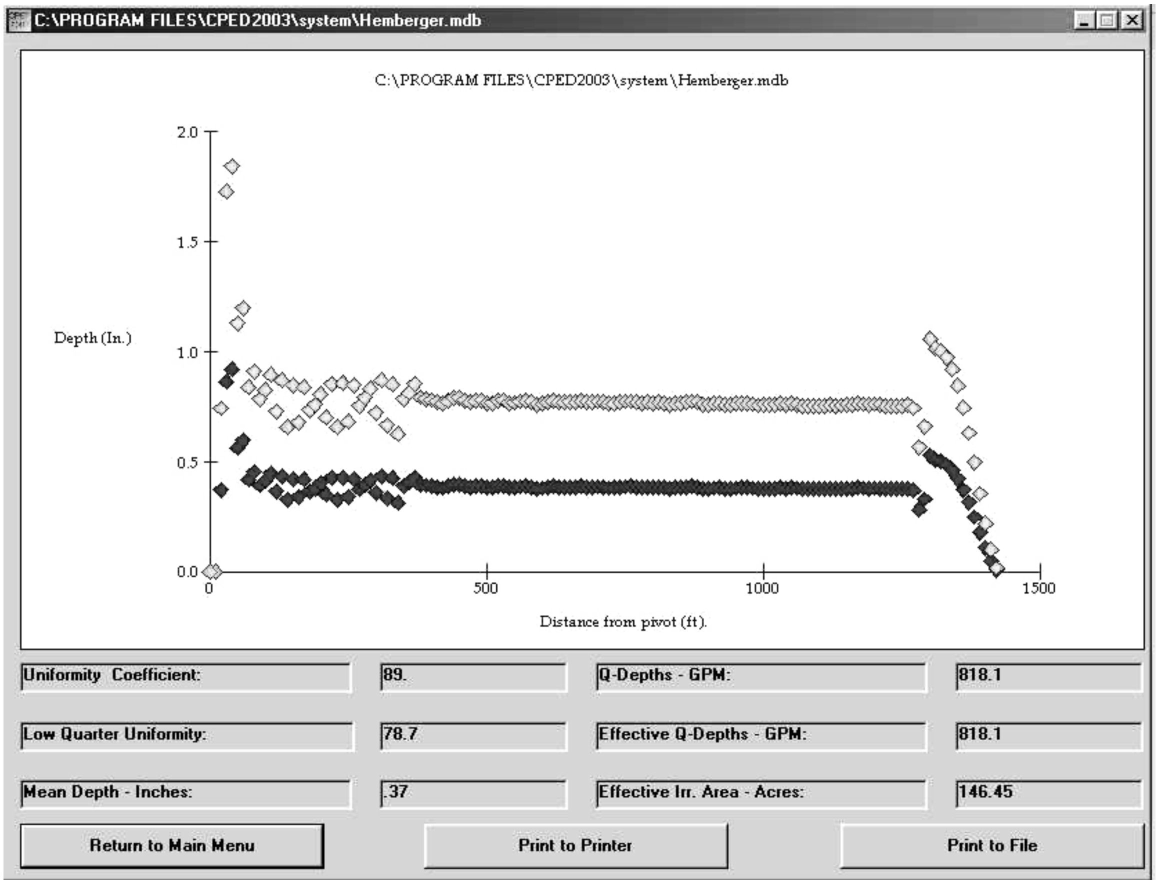
Clicking the *RUN* button will start the simulation. You will automatically be moved to another window that will plot the simulated depth versus distance data on the monitor. Prior to pressing *RUN* you can select a catch can data set or data saved from a previous run to be displayed on the monitor after the simulation is completed. This provides a visual comparison of the current simulation with other data. The data for comparison can be selected from the files listed in the Catch Can File Window. The *Previous Screen* button will return to the Main Window.

You will note a possible selection to Adjust output graph to starting distance. This is normally not needed when simulating the entire system. Clicking this selection is beneficial if you are not simulating from near the pivot and want the plot to begin at the starting distance instead of 0.

SIMULATION OUTPUT WINDOW

The output window plots the simulated depth versus distance from the pivot for the parameters set in the run window. The Coefficient of Uniformity, the Distribution Uniformity, and mean application depth are printed. The Q-Depths, gpm, is the discharge calculated from all simulated depths while the Effective Q-Depths, gpm, is calculated from the depths that are above the specified minimum depth used in the Uniformity and mean depth calculations. The effective area is the simulated area for those areas receiving more than the minimum depth between the starting and stop distances. The window below is an example of plotting catch can data from a previous simulation run.

Additional data can be printed either to the printer or to a file. The *Return to Main Menu* button will return to the main menu screen. The *Print to File* button will ask for the file name for storing the information. You will then be prompted for saving the individual



sprinkler and tower data followed for a prompt to save the simulated
depth data and the name for its file. The saved simulated depth data are then available for comparison with future simulations for the same center pivot system.

The following information can be printed to the printer after the simulation run.

1. The head per stage of the pump - gpm
2. The pivot pressure - psi
3. The system discharge based on the pump curve - gpm
4. The system discharge based on all the integrated depths - gpm
5. The system discharge based on all depths above the minimum depth - gpm
6. The effective irrigated area, which is the area receiving water above the minimum depth - acres
7. The mean depth - in. (of all depths above the minimum)
8. Christiansen's uniformity coefficient (of all depths above the minimum)
9. Mean low quarter uniformity (of all depths above the minimum)
10. Plot of depth vs distance

The information that is available for each sprinkler is the line pressure - psi, the nozzle pressure - psi, the discharge - gpm, and the pattern radius - ft.

The application depths are the final piece of information provided. They are listed by distance.

The *Previous Window* button saves the changes to the system file and returns to the main program window.The *Previous Window* button saves the changes to the system file and returns to the main program window.

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USING CPNOZZLE FOR SPRINKLER FOR SPRINKLER PACKAGE SELECTION

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INTRODUCTION

Center pivots have been adapted to operate on many different soils, to traverse extremely variable terrain, and to provide water to meet a number of different management objectives. Consumers have access to an array of different sprinkler types. For some fields, many packages will perform adequately. Other fields will have a limited number of to choose from. Sprinkler package selection should be based upon accurate field based information, and careful consideration how the package will interact with cultural practices and system management.

What flow rate?

The system flow rate determines how a number of factors impact system operation. For example, if the flow rate is greater than necessary, the peak water application rate may cause runoff toward the outer end of the pivot lateral but the system can recover from unplanned system downtime. If the flow rate is too low, runoff may be eliminated, but unexpected breakdowns can result in significant yield losses.

There are three important considerations when estimating flow rate requirements: a) environmental factors; b) system downtime; and d) the soil water holding capacity. The most important environmental considerations are the likelihood of rainfall and the peak crop water use rate. NebGuide G89-932 *Minimum Center Pivot Design Capacities in Nebraska* presents a procedure for the determining the minimum net system capacity for Nebraska conditions. A similar procedure can be used for Colorado and Kansas.

Estimated crop water use rates, soil water holding capacity and rainfall data were evaluated for different locations in Nebraska. The analysis identified areas where the system flow rate should be increased to account for lower annual precipitation and greater peak ET rates. Our best estimate is that systems located west of the 20-inch annual precipitation line should have greater flow rates. Table 1 presents the estimated minimum net system capacity required to meet crop demands 90% of the time for regions in Nebraska. The last line in the table provides the system capacity necessary to meet peak water demands 100% of the time. That calculation is based on Equation 1:

$$Q_p = (18.9 \times ET_p \times A \times t_i) / (E_i \times t_f) \qquad \textbf{Equation 1}$$

where:
- Q_p = irrigation system flow rate, gpm
- 18.9 = units conversion constant
- ET_p = peak water use rate, in/day
- A = irrigated area, acres
- t_i = irrigation interval, days
- E_i = irrigation efficiency, decimal
- t_f = irrigation time per event, days

Table 1. Minimum net system capacities to meet crop water demands 90% of the time for the major soil texture classifications and regions in Nebraska[1].

Soil Texture	AWC In/ft	Region 1 gpm/ac	Region 2 gpm/ac
Loam, silt loam or very fine sandy loam	2.5	3.85	4.62
Sandy clay loam, loam	2.0	4.13	4.89
Silty clay loam, fine sandy loam	2.0	4.24	5.07
Silty clay	1.6	4.36	5.13
Clay, sandy loam	1.4	4.48	5.19
Loamy sand	1.1	4.83	5.42
Fine sand	1.0	4.95	5.89
Peak ET		**5.65**	**6.60**

[1] Data taken from NebGuide G89-932 *Minimum Center Pivot Design Capacities in Nebraska*.

The values in Table 1 need to be adjusted for system downtime and the water application efficiency of the center pivot. Downtime can result from regularly scheduled maintenance, load control, system failure, or labor restrictions (manager takes Sunday's off). The downtime experienced due to system failure depends on the current age of the components and how frequently the system is checked. Operators with a shutdown phone alarm will have immediate knowledge when the system shuts down while others may not be aware that the system is down for 8 hours or more. If the system is operated 24/7, each 12 hours of down time requires a flow rate increase of 6%.

Once the net capacity has been adjusted for down time, the gross flow rate required is determined by dividing by the estimated water application efficiency. The system water application efficiency depends on the sprinkler package (sprinkler type and position). Some potential water application efficiencies are provided in Table 2. They are listed as potential efficiencies because they assume that runoff does not occur. Thus, the field conditions will determine the actual water application efficiency.

Table 2. Potential water application efficiencies for different sprinkler packages.

Sprinkler/ Nozzle Type	Potential Application Efficiency
High Pressure Impact	80-85
Low Pressure Impact	82-85
Low Pressure Spray up top	85-88
Low Pressure Spray at truss	87-92
Low Pressure Spray at 3-7 feet	90-95
Low Pressure Spray Bubble mode	95-98

Field data collection

The Soil Survey provides one source of estimates for average water infiltration rates, field slopes and soil water holding capacities. Request that the NRCS provide the soil intake family, and record the average field slope, infiltration rate and the soil water holding capacity information on each mapping unit from the local soil survey book. Record them in a table similar to Table 3.

Some sprinkler packages are selected and installed without a site visit by the sprinkler system provider. Though soil mapping units give some indication of average field conditions, the data may not be sufficiently accurate to make a decision. Therefore, a rough grid topography map (at least 200' x 200') will determine if areas mapped as 7 to 11% slopes are closer to 7% or 11%.

Finally, the site visit can provide valuable information related to tillage and planting practices. A field farmed on the contour can safely use a sprinkler package that would be unsuitable if farmed up-and-down hill. Crop residues left on the soil surface can absorb the impact energy of rainfall and irrigation. Thus, the soil infiltration rate would be more consistent throughout the season. Each of these factors may cause you to make a slightly different decision.

Sprinkler packages should be selected that do not result in runoff. Too often the desire to reduce pumping costs clouds over selecting the most appropriate sprinkler package. The zero runoff goal requires that the sprinkler package be carefully matched to field conditions and to the operator’s management scheme. This requires that the water application pattern of the sprinkler be compared to the soil infiltration rate.

Table 3. Summary of soil characteristics for each mapping unit in a quarter section of land in Pierce County, NE.[1]

Mapping Unit	Drainage Group	Soil Water Capacity (in/ft)	Field Slope (%)	Intake Family	Land Area (Acres)
Co	Moderately Slow High Water Table	2.4	0-1	0.3	42.1
He	Well	2.4	0-1	1.0	23.9
CsC2	Well	2.4	1-7	1.0	11.0
HhC	Well	2.4	1-7	1.0	36.8
MoC	Well	2.3	1-7	0.5	5.3
CsD2	Well	2.4	7-11	1.0	28.0
NoD	Well	2.4	7-11	1.0	1.8
CsE2	Well	2.4	11-17	1.0	11.1

[1] Data taken from Pierce County Soil Survey

ESTIMATING RUNOFF

The **CPNOZZLE** computer program was converted to Visual Basic to provide an opportunity to estimate of how well suited the sprinkler is to field soils and slopes. The program is useful in predicting how much the design criteria should be changed to eliminate a potential runoff problem. For example, if a sprinkler package with a 40-foot wetted diameter produces runoff, the program can be used to determine a wetted diameter that produces no runoff. If you are in the process of retrofitting an old system with a new sprinkler package, the program can be used to select an appropriate system flow rate and sprinkler wetted radius.

Based upon research conducted at the University of Nebraska, the program develops an elliptical shaped water application pattern depending upon the position on the system, wetted diameter of the package, and the system flow rate. The program uses the NRCS Intake Family to estimate the weighted potential runoff for various positions along the system. Data inputs include: 1) system length in feet; 2) system capacity in gpm; 3) application amount in inches; 4) wetted diameter of the sprinkler in feet; 5) soil intake family; 6) field slope in %; and 7) percent residue cover in %. The data inputs can be saved to a file or they will be printed with the output information. When all inputs are entered, the program output can be viewed by clicking on results (Figure 1).

Figure 1. Sample input table for the CPNOZZLE program.

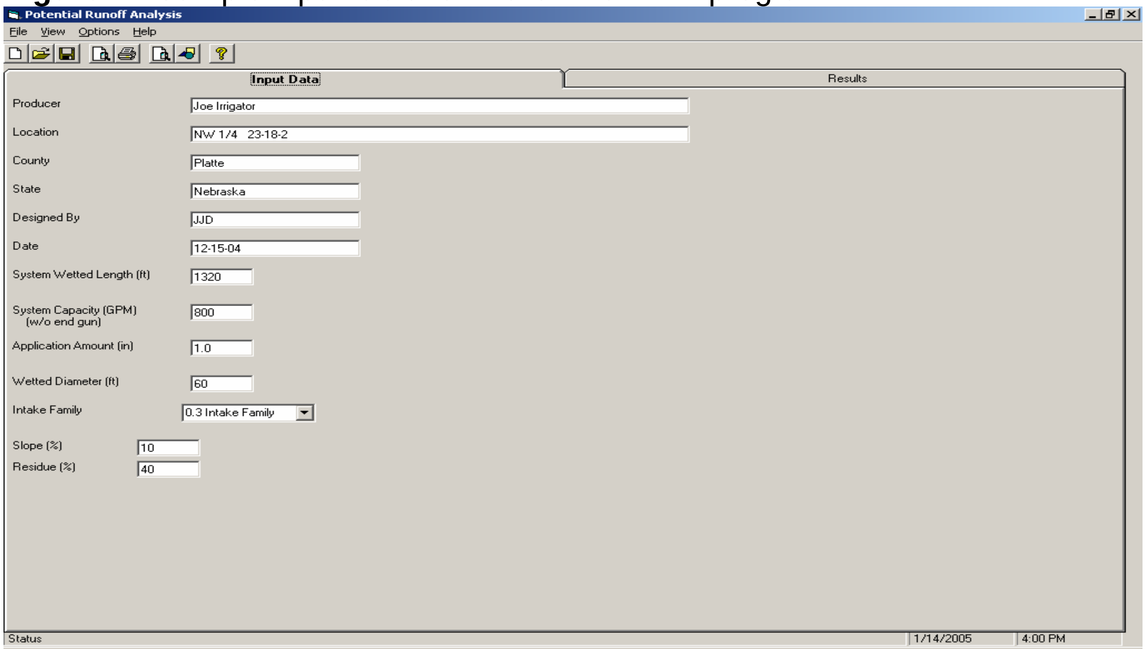
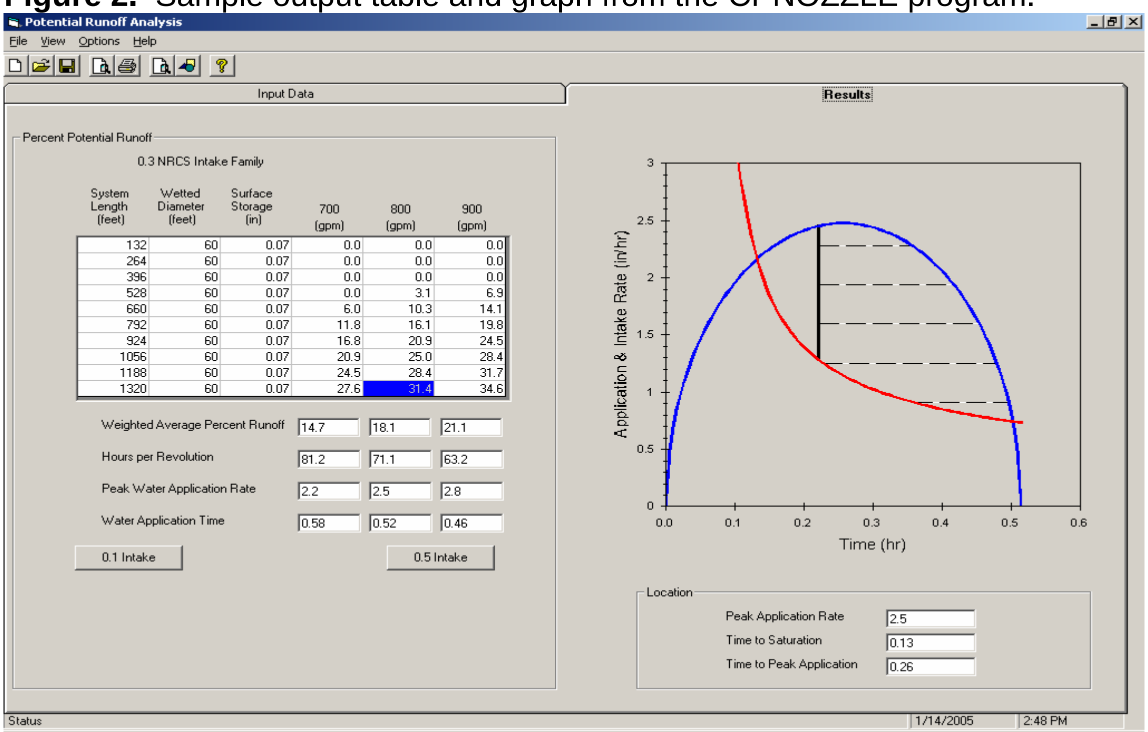


Figure 2. Sample output table and graph from the CPNOZZLE program.



Program output includes a table presenting potential runoff for 10 positions along the system and the weighted potential runoff for the entire field. Output generated for a system with inputs of 1320 foot system, 800 gpm, 1.0 inch application, 60 foot wetted diameter, 0.3 intake family, 10% slope, and 40% residue cover are presented in Table 4. In addition to the inputs listed above, the program also prints results for the same system with a flow rate of 100 gpm more and 100 gpm less than 800 gpm. Results indicate that approximately 18 % of the water applied could move from the point of application or run off the field.

By clicking on the intake family button below the output table, the user can view output from one intake family higher and one lower than the original inputs. The purpose of the additional output is to allow comparisons between different soil intake families and flow rates because few fields have soils that fit into a single intake family. Any of the input information can be changed to perform a 'what if' style of analysis (i.e., if I increase the wetted diameter from 60 feet to 100 feet, What are the results?).

Additional output can include a graphical presentation of the comparison between the water application pattern and the soil infiltration rate curves. By clicking on any of the potential runoff estimates in the table, a graph will appear on the right side of the screen. For example, if the user moves the computer mouse and clicks on the number 25.0 under the 800 gpm column, a graph will appear specifically for the position on the system. In the best-case scenario, the two curves do not intersect.

Table 4. Output table from the CPNOZZLE program for a site in Platte Co., NE

System length feet	**Wetted diameter feet**	**Surface storage Inches**	**700 gpm**	**800 gpm**	**900 gpm**
132	60	0.07	0.0	0.0	0.0
264	60	0.07	0.0	0.0	0.0
396	60	0.07	0.0	0.0	0.0
528	60	0.07	0.0	3.1	6.9
660	60	0.07	6.0	10.3	14.1
792	60	0.07	11.8	16.1	19.8
924	60	0.07	16.8	20.9	24.5
1056	60	0.07	20.9	25.0	28.4
1186	60	0.07	24.5	28.4	31.7
1320	60	0.07	27.6	31.4	34.6
Weighted Average Percent			14.7	**18.1**	21.1
Hours per revolution			81.2	71.1	63.2
Peak Water Application Rate			2.2	2.5	2.8
Water Application Time			0.58	0.52	0.46

Agency and irrigation distribution companies may wish to develop a series of graphs to represent conditions in their area. For example, Figure 3 presents weighted potential runoff comparisons for a range of NRCS intake families when the water application depth increases from 0.5 inches to 2.0 inches per revolution for a 1320 foot center pivot. Inputs of flow rate, sprinkler wetted diameter, field slope, and residue cover were consistent and are presented under the table heading. Note that as application depth increases the potential for runoff increases. However, fields with greater than 5% slope, the application depth cannot be reduced to eliminate runoff without surface storage for soils in the 0.1 to 1.0 NRCS intake family.

Should runoff be predicted, one option is to reduce the system flow rate. Figure 4 presents results for reducing the system flow rate from 800 gpm to 600 gpm. Increasing the wetted diameter of the sprinkler from 40 to 60 feet also helps reduce the potential for runoff. However, though not shown in graphical format, when slopes are above 5% and no crop residues are present, the potential for runoff from low infiltration rate soils is great for the 0.1 to 0.5 Intake Family soils. Impact sprinklers are a better option for fields with steep slopes and low infiltration rate soils.

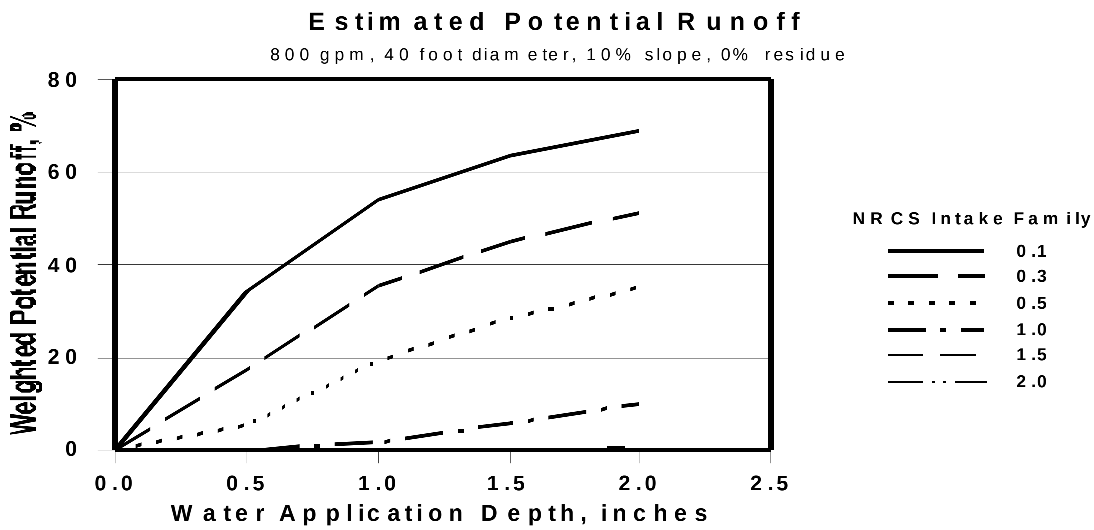


Figure 3. Effect of soil intake family and water application depth on weighted potential runoff for a 1320 foot center pivot with a sprinkler package wetted diameter of 40 feet and a flow rate of 800 gpm.

SUMMARY

Center pivot buyers have a vast array of sprinkler packages to choose from. Selecting the most appropriate sprinkler package for an individual field should be based upon collection of accurate field based information for soils, slopes, and cropping practices. The final selection should not be based on energy costs alone. Rather the system should first apply water uniformly without generating runoff. The new Visual Basic version of the **CPNOZZLE** computer program provides an opportunity to perform 'what if?' sort of analyses prior to making a sprinkler package purchase.

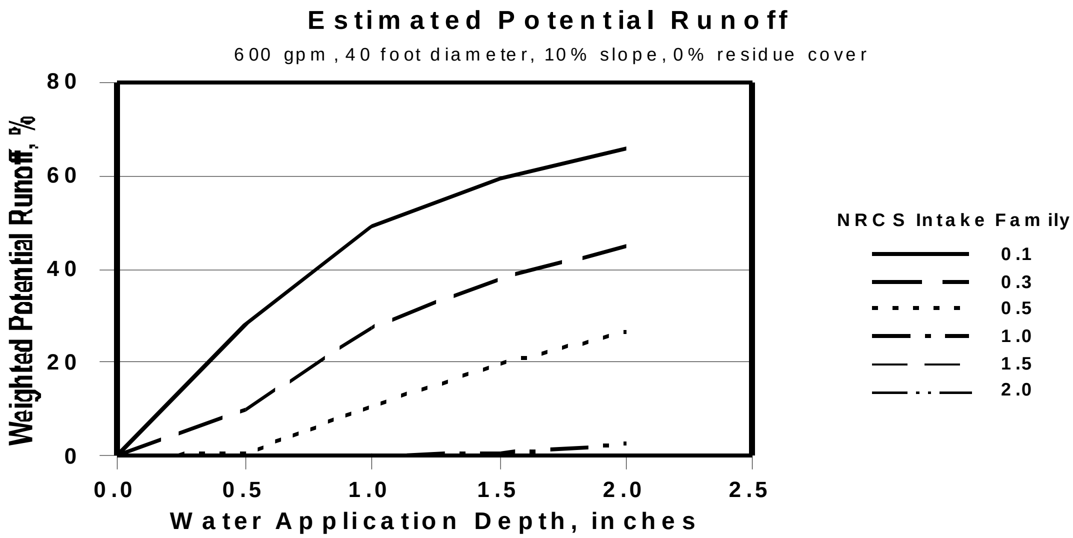


Figure 4. Effect of soil intake family and water application depth on weighted potential runoff for a 1320 foot center pivot with a sprinkler package wetted diameter of 40 feet and a flow rate of 600 gpm.

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