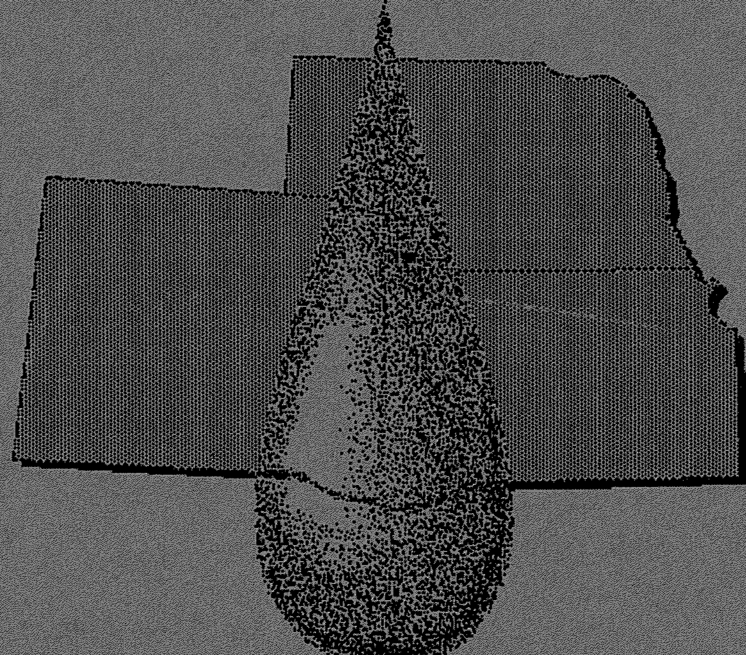
15th Annual

Central Plains Irrigation Conference & Exposition

Proceedings



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WHAT HAPPENED IN 2002?

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INTRODUCTION

Drought was a major event in 2002. During the summer months, more than 50% of the United States was experiencing drought. This was the greatest spatial extent of drought across the country since the mid 1950s. According to the July 23rd Drought Monitor map, drought or abnormal dryness was occurring in all 50 states of the United States.

The 2002 drought was actually a continuation of a series of drought years for the U.S. that began during the La Niña event of 1998. That year was the first of five consecutive drought years for Georgia and South Carolina, and major fires burned across northern Florida that year. The following year, 1999, saw a major drought develop in the eastern U.S. During 2000, drought spread across large sections of the South, Great Plains, and western U.S. More acres were burned by wildfires during 2000 than in any year in the previous 50 years. The Pacific Northwest saw a major drought during 2001, with drought also redeveloping along the East Coast.

As 2002 progressed, drought receded in the Pacific Northwest. However, major droughts developed across the eastern U.S., the Great Plains, and the Inter-mountain West from Montana to Arizona and New Mexico. The drought reached its peak intensity and spatial extent during the summer months. The acres burned from wildfires nearly reached the 2000 level, with the largest wildfires in state history occurring in Colorado, Arizona, and Oregon. During the fall of 2002, a series of storms hit the eastern United States, improving drought conditions there. The year ended with 2002 being the driest year on record (108 years) for Colorado; the 3rd driest for Nebraska, Wyoming, and Nevada; 4th driest for Arizona; 7th driest for Utah; 13th driest for South Dakota; and 19th driest for Kansas.

At the beginning of 2003, very little drought remains in the East. However, major drought problems continue across the Great Plains and the Rocky Mountain states, with additional dryness occurring in parts of the Great Lakes.

2002 DROUGHT IMPACTS

Because of the complex characteristics of drought, it has always been difficult in the past to quantify drought impacts, especially the economic losses. During 2002, drought impacts were felt across the following sectors: agriculture (crops, livestock, timber), environment (endangered species, water quality, soil erosion/degradation, wildlife intrusion), recreation, tourism, wildfire, water supply, public health, and energy. Some of the specific drought impacts from the 2002 drought include:

- low water supply issues from east to west led many localities to request voluntary or issue mandatory water restrictions; for example, in Colorado, 5 communities experienced water supply emergencies and 19 reached "critical" designations;
- low well levels or dried up wells; 18,000 families in Maine had their wells go dry at some time between August 2001 and June 2002;
- widespread record or near-record low streamflows in many areas of the U.S.;
- dismal snowpack in the Rockies, Southwest, and parts of the Great Basin;
- barge traffic threatened on the Missouri River as well as recreation and environmental interests in the basin; the river fell 9-15 feet below normal in average depth according to the U.S. Army Corps of Engineers;
- very active fire season, with 7.1 million acres burned for the year, nearly twice as much as the 10-year average to date and the second highest total in 50 years (according to the National Interagency Fire Center); costs to fight fires estimated at $1.25 billion;
- Denver Water estimated that it would lose $14 million in revenue in 2002 because of drought in Colorado;
- more than 7,000 stock ponds went dry across the 17 million acres of the Navajo Indian Reservation;
- a mild winter followed by hot and dry weather was ideal for grasshopper infestations in Nebraska, South Dakota, Colorado, New Mexico, Idaho and Oregon; although these states have been hit the worst, outbreaks have been seen in parts of most states west of the Mississippi River;
- elk populations in New Mexico were expected to fall by 10,000 from 2001 levels; additional wildlife impacts widespread across the U.S.;
- the U.S. saw its lowest winter wheat crop since 1971 with the smallest harvested acreage seen since 1917;
- national pasture/rangeland conditions in 2002 were the worst since record-keeping began in 1995;
- farmers and ranchers have been facing a shortage of forage for livestock; a lot of culling has taken place in many states in the Plains and West; the Colorado cattle breeding stock was reduced by 50% in 2002;
- USDA Secretary Ann Veneman announced the opening of all CRP land in all states, as well as a variety of additional USDA programs;
- according to USDA/NRCS, a record low water supply forecast was issued for the Rio Grande Basin. For the forecast point of Del Norte, CO, the April-Sept. runoff estimate was 90,000 acre-feet; since the USGS started collecting

streamflow data at this gage in 1890, the record low runoff for this period was 155,700 acre-feet in 1977.

Economic loss estimates from previous droughts are almost non-existent. Riebsame et al. (1991) made a rough estimate that the 1988 drought totaled $39.2 billion in losses. Some states, however, have done a better job estimating losses during 2002 and the estimates that do exist are included in Table 1. The estimates are derived in a variety of ways, highlighting the need for a consistent approach that can be applied nationally. The approximate total from the table is $11.22 billion, although it is certainly not complete with many states and sectors still absent in that total. As a result of drought in parts of Missouri during 2002, for example, the state formed an Economic Impact Committee to look at establishing a comprehensive process for accurately estimating the economic losses due to drought.

Table 1. Economic Loss Estimates Caused by Drought During 2002.

State	Estimate	Sector	Comments
Colorado	$1.1 billion $460 million	Agriculture Livestock	
	$1.7 billion $200 million $800,000	Tourism Outfitters Fishing licenses	Summer only
Kansas	$1.4 billion $300 million	Agriculture Livestock	
Montana	$2.0 billion	Agriculture	
Nebraska	$1.2 billion	Agriculture	
North Carolina	$398 million	Agriculture	Crop losses
	$15-20 million	Municipalities	Water revenues
Oklahoma	$1.0 billion	Agriculture	Includes 2001
South Carolina	$84 million	Agriculture	Crop losses
	$250 million	Timber	Southern pine beetle
South Dakota	$1.8 billion	Agriculture	
	$23 million	Environmental	Missouri River
Utah	$250 million	Agriculture	
Wyoming	$1.8 million $161,538	Wildfire suppression Value loss	

Several other drought loss estimates have been made for 2002. An initial figure from USDA estimates approximately $4.4 billion in crop insurance payments around the country. Officials around Lake Mead above Hoover Dam estimated $970,000 in losses due to drought though October 2002. Because of the costs to reconfigure the recreational facilities around the lake, an additional $400,000-800,000 will be lost with each 20-foot drop in the lake levels.

NATIONAL DROUGHT POLICY RESPONSES IN 2002

Assisted by drought conditions across large parts of the country, the United States Congress looked at three major pieces of drought-related legislation during 2002. The first bill was introduced by Senator Pete Domenici (New Mexico) in the Senate and Representatives Alcee Hastings (Florida) and Denny Rehberg (Montana) in the House during May and was called the National Drought Preparedness Act. The bill encouraged drought planning and mitigation activities, and would have formed a National Drought Council to oversee some of these activities and to coordinate the federal responses to drought, which have historically been poorly timed and ineffective. The seriousness of the drought (diverting attention to drought relief and away from drought mitigation and preparedness) and the lack of federal leadership caused this bill to lose momentum and stall as the year ended. It may be reintroduced in 2003.

The need for drought relief for large areas of the country helped the Senate pass the $5.9 billion Drought Relief Act. Opposition from the White House helped keep the bill from passing in the House, however. Finally, the Small Business Administration Drought Relief Act would have allowed SBA to assist tourism- and recreation-related businesses hurt by drought. At this time, SBA does not recognize drought as a natural disaster, and therefore cannot provide assistance to these businesses, which have been especially hurt during the past several years of drought.

USDA did provide programs for drought relief during 2002. USDA Secretary Veneman took the unusual step in August of releasing all CRP land across the country for emergency haying and pasture. USDA also provided a livestock assistance program in September for suffering ranchers in Wyoming, Colorado, Kansas, and Nebraska. By the time 2002 had ended, 1,837 counties across the country had been declared as primary agricultural disaster areas, with an additional 484 counties also eligible for relief by being contiguous to the declared counties. All counties in both Kansas and Nebraska were declared as primary agricultural disaster areas.

LOCAL DROUGHT RESPONSE IN 2002

Nebraska responded aggressively to the drought in 2002 as it began to intensify in the spring. The state had recently revised its drought plan to include mitigation actions in 2000. These mitigation actions had successful outcomes during 2002. One of the actions was to establish hay and farmer stress hotlines as conditions developed. Both of these hotlines were quickly implemented and provided important resources to the producers around the state. The state also targeted "vulnerable" communities with potential water supply problems in 2000. Working with the communities, and offering workshops and various forms of assistance, fewer communities suffered water supply problems during 2002 than during 2000 across the state despite the fact the drought was more severe. The state had also improved its drought monitoring capabilities in recent years, which helped during the 2002 drought. Lessons learned from 2000 also helped improve the coordination and communication between county, state, and federal officials in 2002. Finally, the University of Nebraska Cooperative Extension had established the backbone of a drought-related website during 2000 that became very easy to re-activate and improve during 2002.

Colorado also recently updated their state drought plan to incorporate mitigation activities. The drought plan was activated completely during 2002 for the first time since it was originally adopted in 1981. Lessons learned during 2002, and 2003 if the drought continues, will help encourage the state to implement the mitigation strategies it has recently included within its drought plan. During the year, Colorado State University and the University of Colorado combined resources and expertise to form a Drought Research Center with the objective of investigating the impacts of drought on Colorado, particularly the potential impacts from multiple-year droughts.

Kansas is one of a handful of states that does not have a drought plan document. Officials have generally been confident and satisfied with their drought response capabilities during droughts in the past. With the trend across the country to begin to adopt mitigation strategies to reduce natural disaster losses, a trend that has recently gained momentum with drought as well, developing a drought mitigation plan for the state could be an important next step in dealing with droughts across the state. It is certainly a suggestion that is encouraged by the National Drought Mitigation Center.

CONCLUSION

Drought in 2002 definitely illustrated that the country remains highly vulnerable to drought impacts, and that mitigation strategies are needed to help begin to address, and hopefully reduce, these impacts in the future. The need for drought mitigation and preparedness exists at all levels: federal, state, local, regional, and tribal. It remains to be seen whether or not the lessons learned from the 2002 drought will move officials across the United States in this direction toward drought mitigation and preparedness.

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LONG-TERM EFFECTS OF THE DROUGHT ON THE CENTRAL GREAT PLAINS

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INTRODUCTION

Much of the US Central Great Plains is in the midst of a drought that started in 2000 and has persisted through today, 2003. Although the drought areas shift about and there is sometimes some temporary relief, the persistence and severity of the drought has made successful dryland crop production nearly impossible and even strained many of the irrigated production systems. Questions have arisen about the long term effects of the drought. My remarks will be confined to drought effects on crop production and on the Ogallala. Therefore, my remarks will not specifically address the very real problems of wind erosion hazards and of individual financial strains and bankruptcies. These indeed can have long term effects.

WHAT EFFECTS ARE BEING OBSERVED?

In my opinion, we are in a historical drought situation. By that I mean, this extreme drought has not been seen by most of us still actively engaged in farming and ranching and that it will be a story we are likely to refer back to by, "We—ll, I remember back in 02, it was so dry........". Now, having implied that these are rare conditions, let me point out that with our present situtaion, 2003 could be just as bad or worse.

The drought of 2002 was an *Equal Opportunity Drought* in that it had broad conditions:

- Widespread across Central Great Plains
- Affected both dryland and irrigated areas
- Affected all irrigation system types
- Affected winter and summer crops
- Affected all crop types

In mid-summer 2002, all of Colorado was in extreme or exception drought. Nearly all of Nebraska was in severe to exceptional drought and nearly 2/3 of Kansas was in moderate to exceptional drought (Figure 1). Dryland crop production even with conservation tillage systems often were a disaster in 2002, particularly for corn (Figure 2.) which has less tolerance for extreme drought compared to grain sorghum and sunflowers.

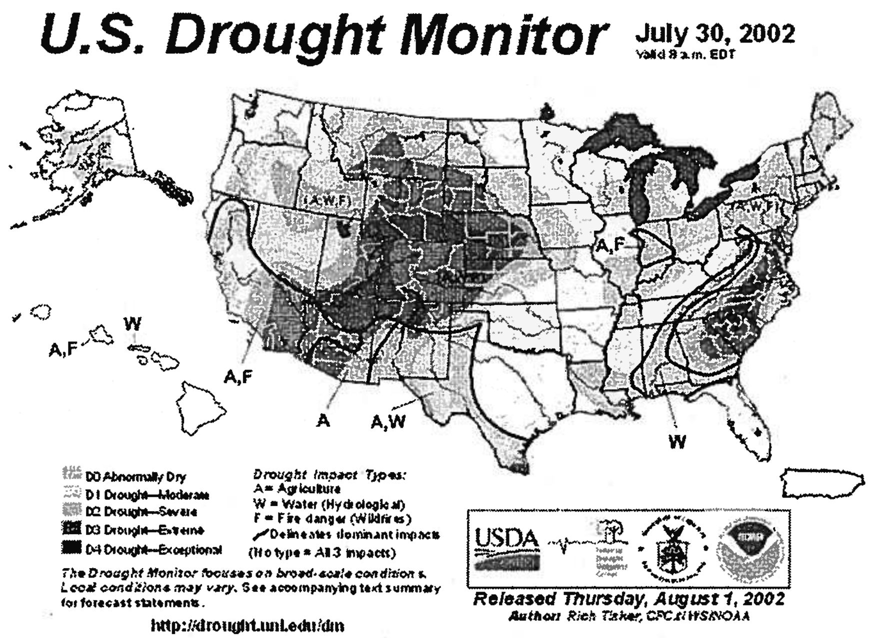

Figure 1. US Drought Monitor for July 30, 2002. Source of graph, National Drought Mitigation Center, http://www.drought.unl.edu/

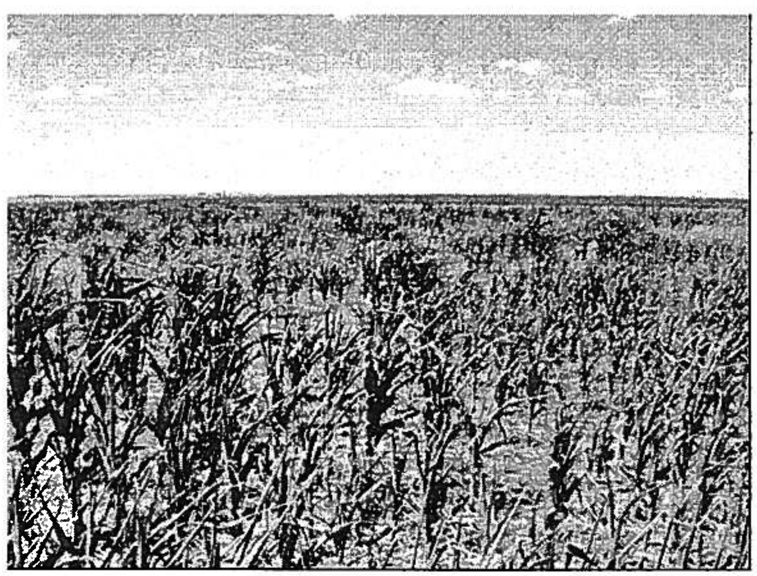

Figure 2. Failure of the dryland corn leg of the wheat-corn fallow system in 2002, Colby, Kansas.

The severity of the drought in 2002 affected all types of irrigation systems.

- Center pivot irrigation systems
  Problem in 2002: Erratic crop height, pollenation and grain fill.
- Furrow (Flood) irrigation systems
  Problem in 2002: Difficulty staying within water right; Water stress between infrequent events.
- Subsurface drip irrigation (SDI) systems
  Problem in 2002: Lack of surface soil water for germination

Since center pivot sprinkler irrigation is the predominate irrigation system in the Central Great Plains, there was obviously a more easily seen and recognized problem with them. Tremendous differences in crop height, pollination and grain fill were even observed over very short distances (Figure 3 and 4). Many of these differences are attributed to slight amounts of runoff and runon occurring within the field. Although these differences probably existed for the problem fields in previous years, more average rainfall and lower evapotranspiration would allow these differences to be masked out. A good way to characterize this problem is to consider a planned irrigation amount of 1 inch. If only 1/10 inch runoff occurs from a small high spot and then runs into a microdepression, now you have nearby areas receiving 1.1 inches and 0.9 inches, a 22% difference in irrigation. Compounding this problem over the course of the season by multiple events, resulted in the extremely erratic corn production we experienced under center pivot sprinklers. The major cause of runoff and runon under sprinklers is too high an irrigation application rate for the soil conditions. High application rates are a potential problem under many incanopy sprinkler irrigation systems, because the wetted radius of the sprinkler is greatly distorted and reduced by the crop canopy. We would expect runoff/runon problems to be worse with widely spaced incanopy sprinklers, poorly regulated sprinkler packages, undulating slopes, and conventional tillage. Examination of many of the problem fields in 2002 showed some of these same design and operational characteristics. An easy way to determine if runoff/runon occurred was to go to an area in the field where the sprinkler had passed over within the previous day or two. You could observe wet damp soil in runon depressions by kneeling down and looking at the microrelief. Another way was to look for a flush of small late season grasses in areas receiving slightly more irrigation. Some of these characteristics are solvable problems that irrigators could avoid, should 2003 be a twin to 2002. The economic benefits of correcting a sprinkler package or spacing problems in a year such as 2002, would dwarf the added costs of correcting the problems. Research conducted at the KSU Northwest Research Extension Center at Colby, Kansas (Yonts et. al., 2003) has shown row-to-row yield differences can be as high as 10-15 bushels/acre for incanopy sprinkler irrigation with 10-foot spaced nozzles. In 2002, these differences could have been greater.

Figure 3. Erratic height and ear size differences over very short distances in center pivot sprinkler irrigated corn in 2002, Colby, Kansas.

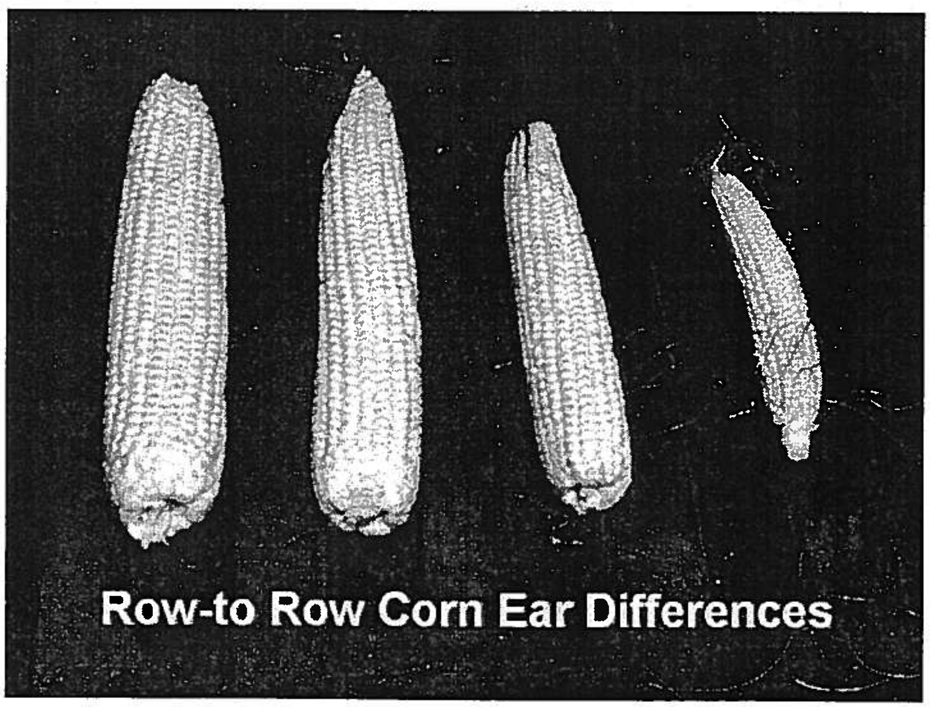

Figure 4. Drastic differences in row-to-row ear size for sprinkler irrigated corn in 2002, Colby, Kansas. Note: Ears from same area depicted in Figure 3.

Often a group of relatively small or unrecognized sprinkler problems combined negatively to add up to a major problem in 2002. Figure 5 depicts a poor yielding area in a field where three additive sprinkler problems existed. This combined problem has probably existed for years, but only became strongly recognizable in 2002.

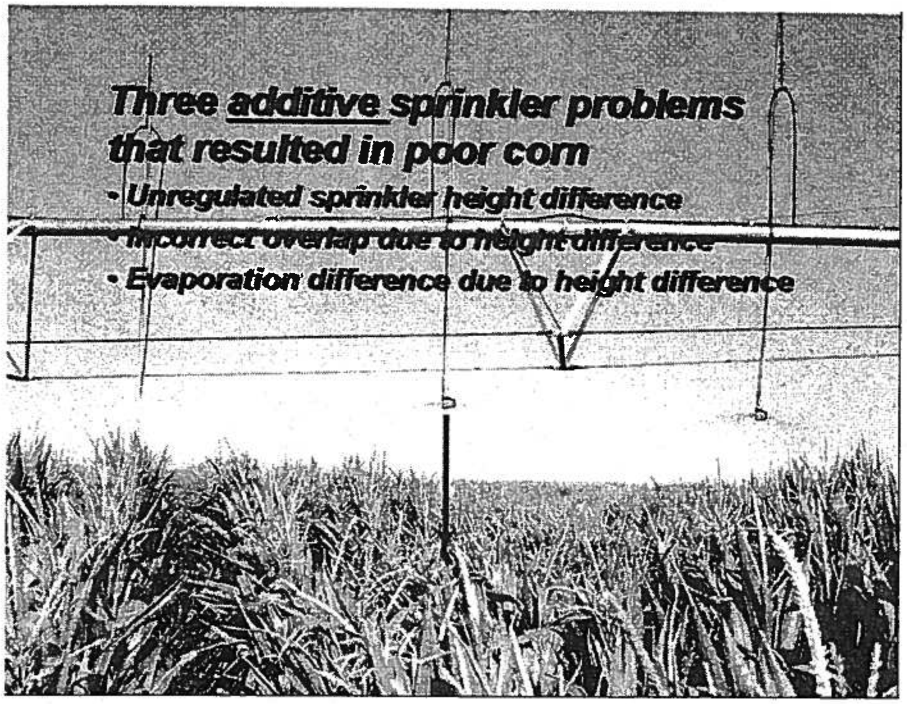

Figure 5. Poor yielding corn under a sprinkler nozzle in 2002, Colby, Kansas. The three problems that caused the reduced yield are sprinkler height differences (approximately 2 ft) with no pressure regulators, incorrect overlap due to height differences and the evaporation difference due to the height difference. Since the system had a relatively low operating pressure (15 psi) it would be presumed that the lack of pressure regulation on the height difference is the major cause of yield reduction.

Other problems in 2002 involved irrigation wells and pumps experiencing decreased pumping capacity, sucking air and cascading water. Some irrigators have expressed concern that these problems are long-term. In general these problems are probably not long term, but will be discussed later in this paper.

Both winter and summer crops were affected in 2002 and this placed additional financial burdens on the producer already experiencing poor economic conditions. No crop really escaped the wrath of the drought. In some cases, lack of germination stopped the crop from day one.

WHAT IS THE SEVERITY OF THESE EFFECTS?

While the individual factors of lower precipitation, higher temperatures and higher evapotranspiration were all abnormal values, their combining in such a negative fashion resulted in the extreme situation we experienced.

The annual precipitation for 2002 at the KSU Northwest Research-Extension Center was 12.93 inches, approximately 2/3 of the long term average value, but the spring and early summer precipitation was extremely deficient (Figure 6). Very similar drought conditions were also present in 2000 and 2001.

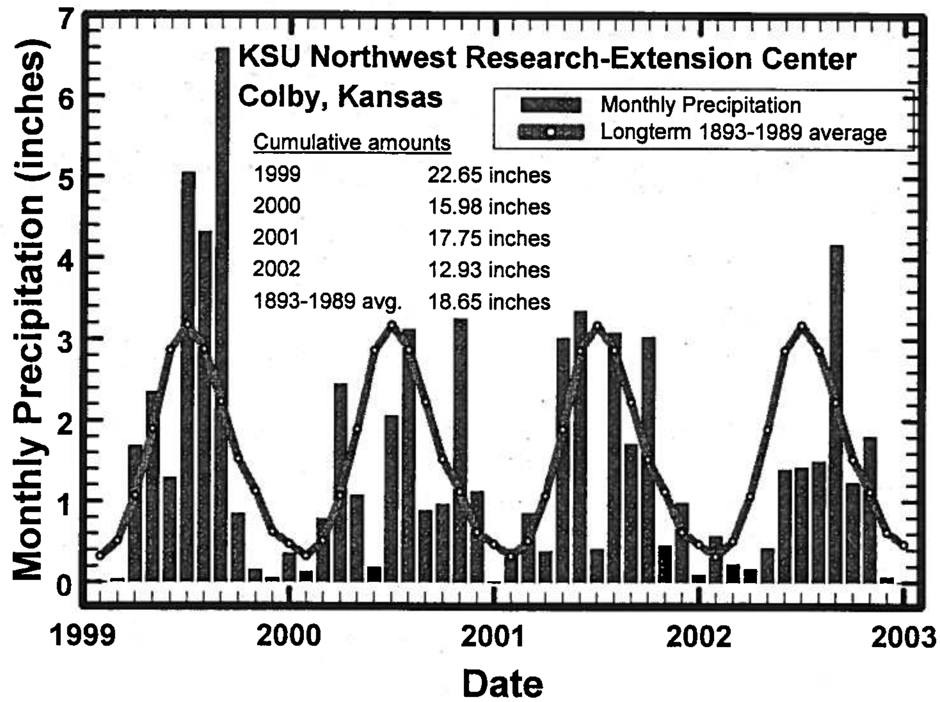

Figure 6. Precipitation patterns at the KSU Northwest Research-Extension Center, Colby, Kansas for 1999-2002.

In addition, elevated temperatures in the early summer (June) and continuing into July (Figure 7.) resulted in larger than normal evaporation and transpiration losses from the soil and crop, respectively. The evapotranspiration for 2000, 2001 and 2002 were all 3 to 4 inches above the long-term average amount (Figure 8).

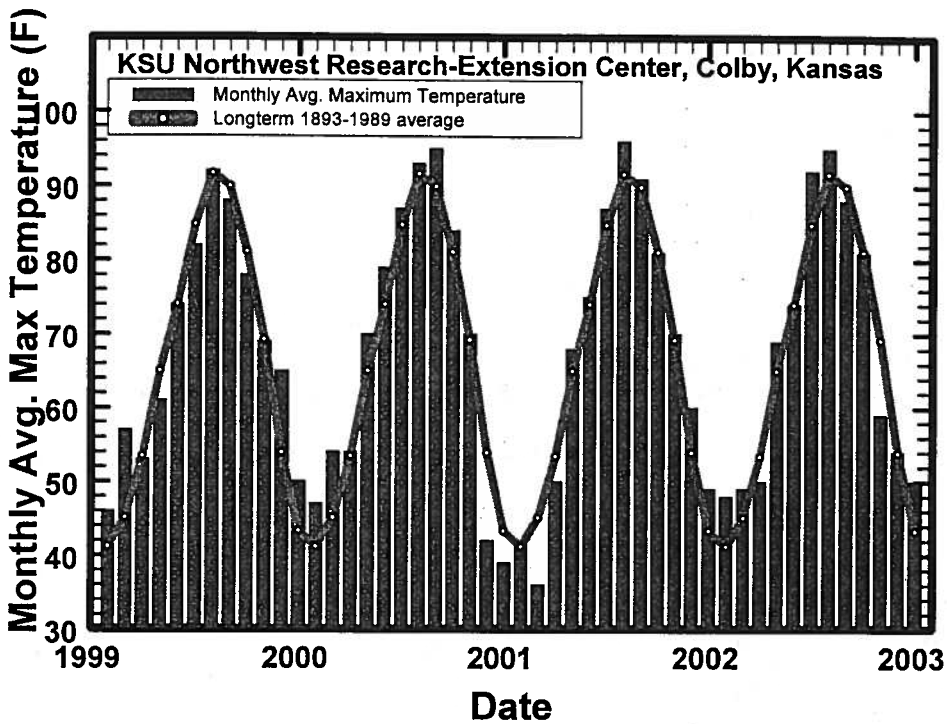

Figure 7. Monthly average maximum daily temperatures for KSU Northwest Research-Extension Center, Colby, Kansas for 1999-2002.

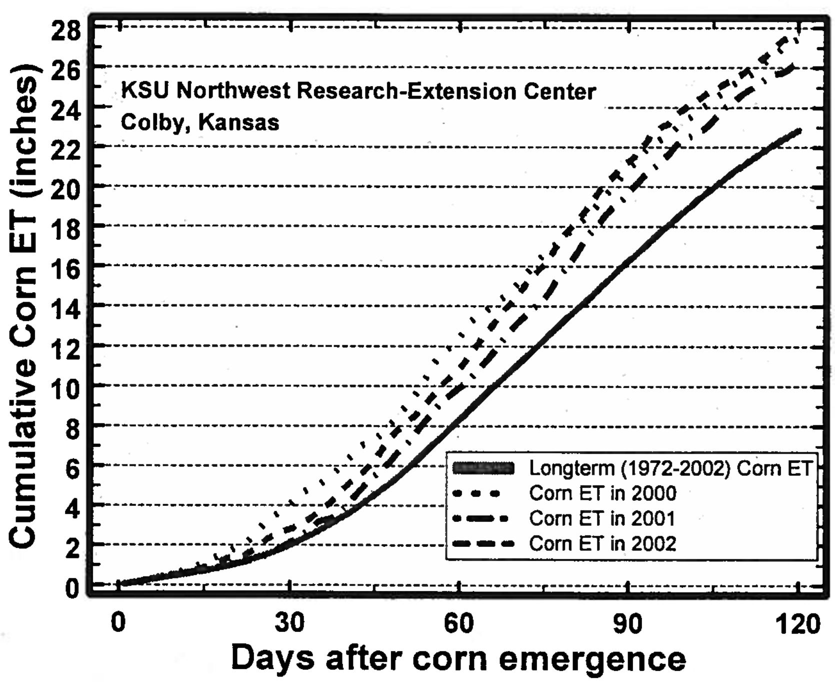

Figure 8. Cumulative corn evapotranspiration (ET) for 2000-2002 as compared to the 30 year average, KSU Northwest Research-Extension Center, Colby, Kansas.

Many irrigation systems in western Kansas do not have the capacity in the typical 90 day irrigation season to apply the irrigation requirements of 2000, 2001 and 2002 Figure 9. Thus, many irrigated corn fields failed or had very poor yields.

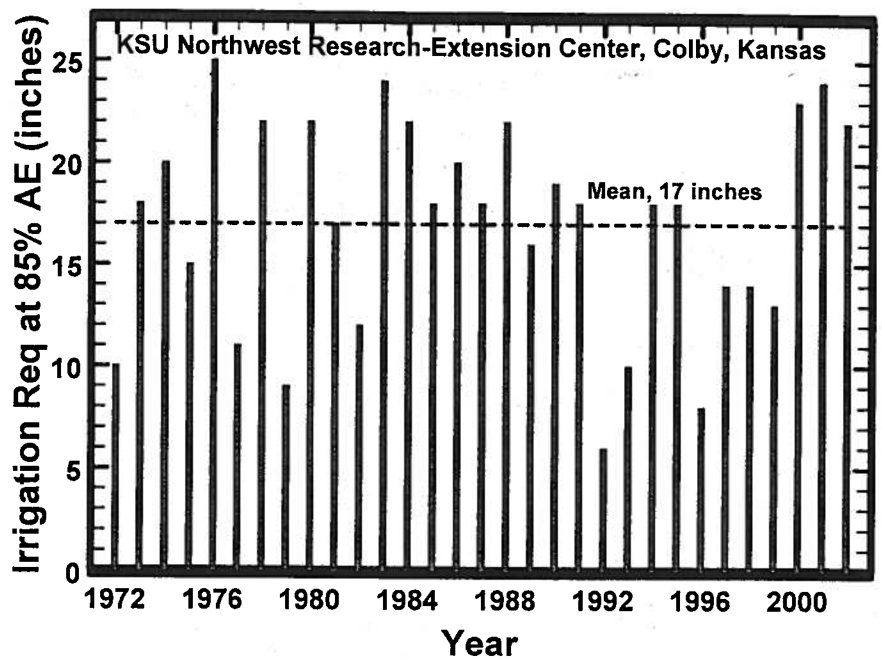

Figure 9. Required irrigation amounts in 2000-2002 were 5-7 inches greater than normal based on simulated irrigation schedules for the KSU Northwest Research-Extension Center, Colby, Kansas.

The problem of decreasing inseason well performance and pumping rates resulted in:

- Increased labor and management to renozzle center pivots.
- Increased water stress due to less capacity.
- Poor uniformity and/or pump damage if not recognized and fixed.

ARE THESE EFFECTS TEMPORARY OR PERMANENT?

Well, it's a good news/bad news situation. The *Good News* is good crop yields will return when more average climatic conditions return. The *Bad News* is the drought continues and the normal winter period precipitation is low, so soil water reserves may be low next spring (Figure 10).

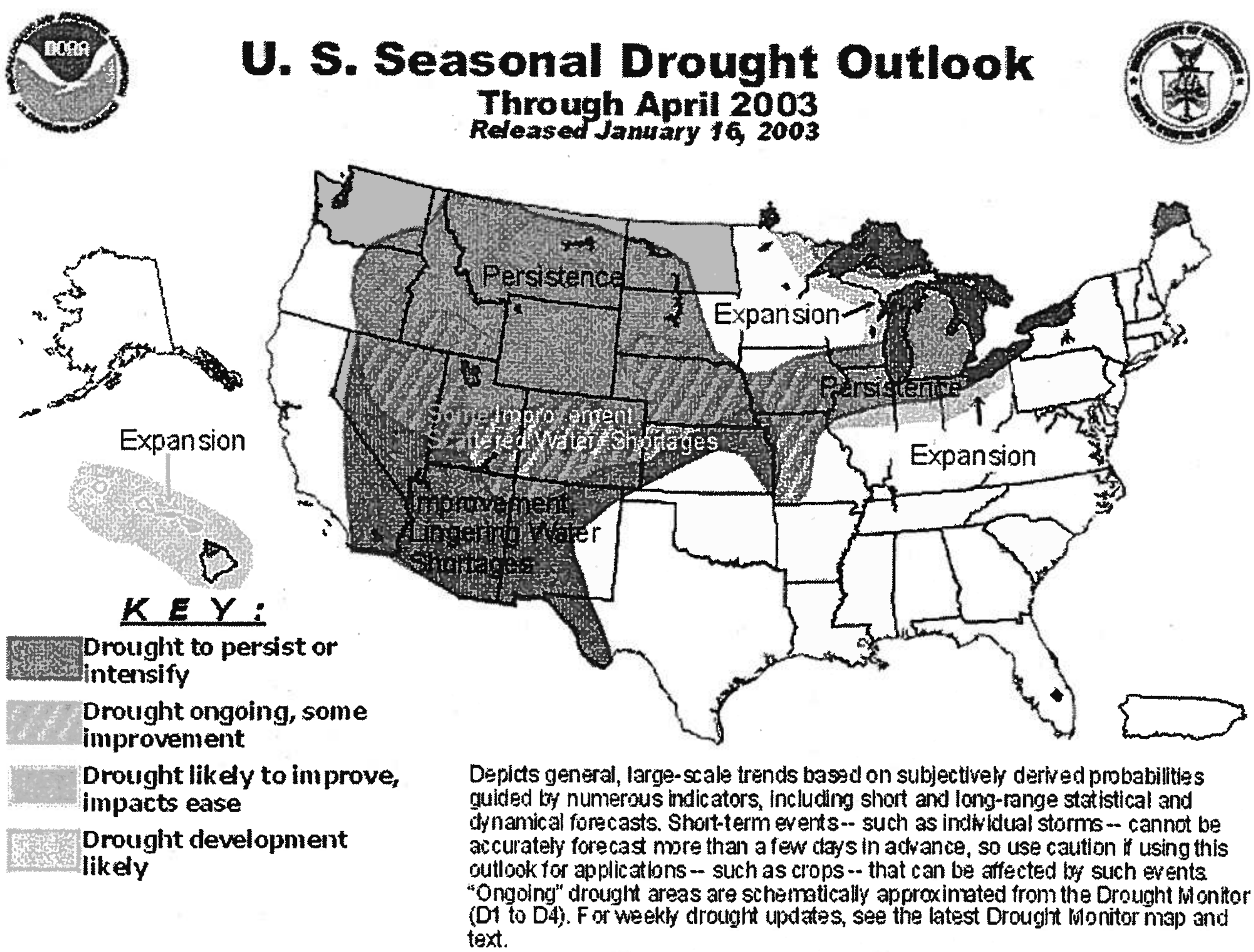

Figure 10. US Seasonal Drought Outlook through April 2003. Source of graph, National Drought Mitigation Center, http://www.drought.unl.edu/

The *Bad News* is increased groundwater use during the drought and for its duration is essentially a permanent loss from the Ogallala. The *Good News* is the Ogallala is still a huge resource and the annual effect of the drought on the aquifer is relatively small.

The *Bad News* is in the future, problems of decreased pumping rates and cascading water will likely increase as groundwater levels further decline. The *Good News* is these effects will be seasonal with considerable overwinter recovery (Figure 11). When the drought ends these effects will lessen somewhat, due to less pumping requirements (time).

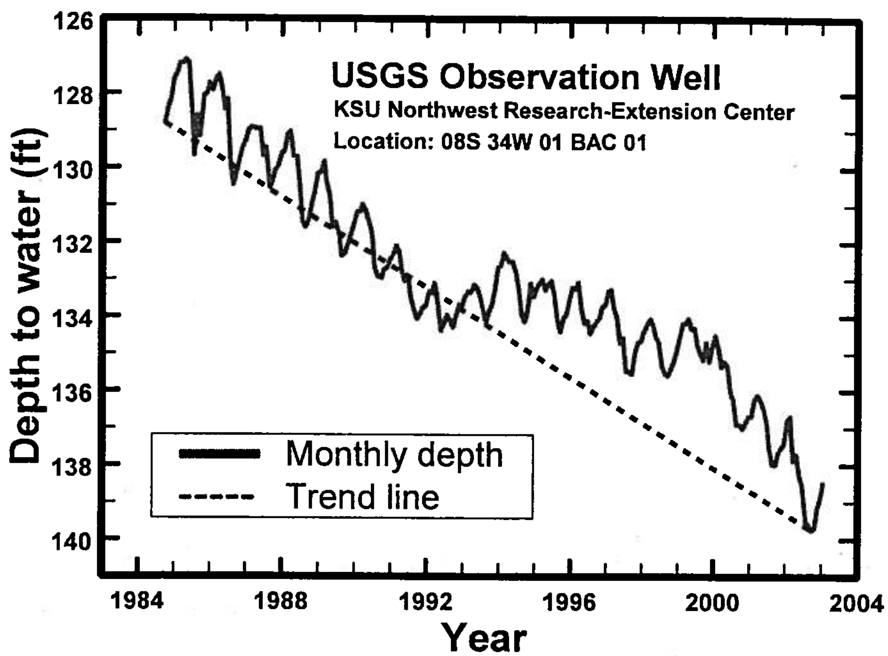

Figure 11. Long term decline in aquifer water levels and partial overwinter recovery of observation well at KSU Northwest Research-Extension Center, Colby, Kansas. Note: Seasonal declines are caused by drawdown.

CONCLUDING STATEMENTS

In summary, the effects on crop production and on the Ogallala are to a great extent temporary. The direct effects on the Ogallala are slow to be realized, so when the drought ends, the scale of these effects is not large. Hopefully, the greatest effect will be social--the renewed understanding of the value of water and its importance in Central Great Plains.

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A REFLECTION ON IRRIGATION CHANGES

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INTRODUCTION

Irrigation has been practiced for many years perhaps first in Egypt several thousand years ago. There is evidence of irrigation in North America that dates back to the year 500 A. D. These systems had evidence of many irrigation ditches moving water from the rivers to the fields in the surrounding valleys. Morgan, 1993 wrote a history of American irrigation titled "Water and the Land." Morgan recognized the irrigation of nearly 200 years ago but wrote that the modern era of irrigation in the United States began in the mid-19th Century as American pioneers moved West. He attributed the teaching of the first college irrigation course in 1883 to Elwood Mead at the Agricultural College of Colorado in Fort Collins. After leaving the college Mead continued his irrigation work for the U. S. Department of Agriculture and as a commissioner of the Bureau of Reclamation. The lake formed by Hoover Dam is named Lake Mead after this agricultural engineer. As a scientist with the Water Management Unit of the USDA in Fort Collins we can trace our roots back to Elwood Mead.

The objective of this paper is to review the evolution of modern irrigation technology in the United States and the Central Great Plains. The major focus will be the last century.

IRRIGATION TECHNOLOGY IN THE EARLY 20TH CENTURY

Irrigation development prior to 1900 in the United States was primarily by local irrigators. They were close to the streams and diverted water to the adjacent land. The United States Bureau of Reclamation (USBR) was established in 1902 to encourage development of the West and migration to the unpopulated area. Without the government policy and goal to populate the West, we would have less area irrigated in the West. Today, approximately 29% of the total irrigated area in the United States is supplied water from USBR projects. Surface irrigation was the dominant method for practically all irrigation systems older than a century. This would be true for all irrigation systems around the world. It is only during the last 70 years with the advent of deep well turbine pumps, combustion engines, rural electrification, sprinkler and drip irrigation systems that we have seen a significant change from the surface diversions and surface irrigation systems. It was the later changes that dramatically changed the irrigation in the Central Great Plains.

Surface irrigation was the primary method of irrigation. Furrow irrigation typically used earthen ditches and the irrigator would cut the ditch bank or siphon tubes were beginning to divert the water into individual furrows. Tractors became available to level the land, a significant change from the use of horses prior to 1900. The irrigation technology was limited to the existing materials and technology of the time. Sprinkler irrigation systems were being developed in the early 1900's but were quite limited until after World War II. Aluminum was used extensively for the development of airplanes and other equipment used during the war. When it became available to agriculture and industry was looking for a market; gated pipe and hand move sprinkler systems were brought to the market. It was then that all of agriculture became much more mechanized.

IRRIGATION TECHNOLOGY IN THE LATER PART OF THE 20TH CENTURY

It is this time period that we have seen major changes. We were in the Industrial Age and mechanization advanced rapidly in agriculture. The light weight pipe decreased the work for hand move sprinkler systems and contributed to their large increase in popularity. A significant increase in aluminum gated pipe and siphon tubes reduced the labor for furrow irrigation compared with cutting ditch banks. Without this technology and available material, we may have not seen this change take place. The advent of deep well turbines and right angle drives allowed ground water to be developed for irrigation. Without these technologies, much of the Central Great Plains would not have been developed for irrigation. Figure 1 shows the trend of irrigation systems in the last 30 years.

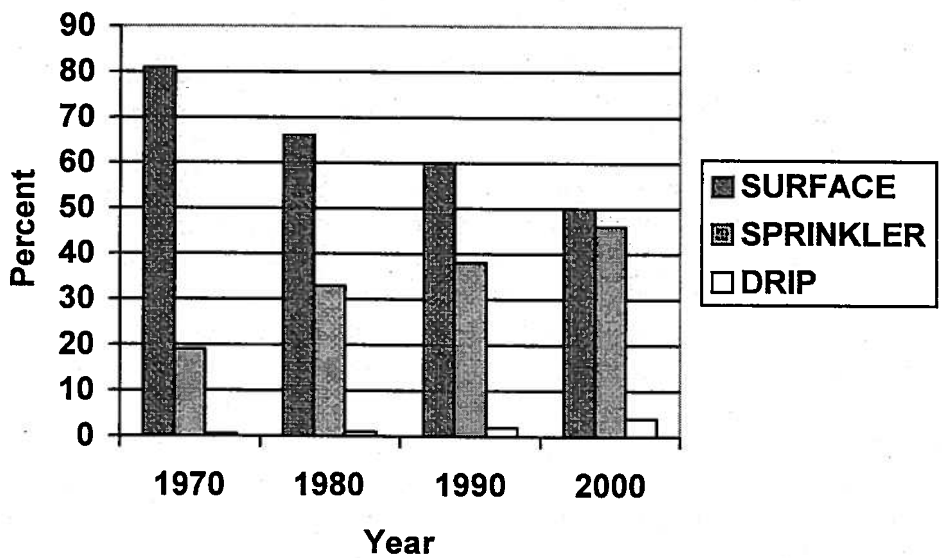

Figure 1. United States Irrigation Statistics.

The center pivot sprinkler irrigation system was invented in 1952. It was in the 1960's when the large scale adoption began and Daugherty (1970) reported that there were approximately 8000 systems in operation by 1970. He was concerned about the lack of governmental support for center pivots in contrast to their efforts to promote and improve furrow irrigation. However, today there are 17.3 million acres irrigated with center pivots in the United States (1998 Farm and Ranch Irrigation Survey, http://www.nass.usda.gov/census/census97/fris/fris.htm) or about 33% of the total irrigated acreage. This is in contrast to the reduction from 81% to 50% of the area irrigated with surface irrigation systems. In the Central Great Plains 62% of the irrigated area is under sprinkler irrigation. Forty percent of the area irrigated with center pivots are in the three Central Great Plains States. Why this rather rapid change? I believe the factor causing the change is the greatly reduced labor for irrigation with the center pivot. Since the 1950's, farm equipment has been increasing in size and the only way producers can be profitable is to increase the size of farms. This trend has made it imperative that the irrigation systems also be able to irrigate larger areas with reduced labor.

The competition in manufacturing center pivots has led to the development of reliable and efficient systems. The number of center pivot manufacturers was in excess of 20 during the 1970's. Only in the past 10 years has the number of manufacturers became more stable with less than 10 companies manufacturing most of the new systems. Clearly, a majority of the center pivot systems are manufactured in the Central Great Plains states. However, the large number of manufacturers did provide many new ideas that has contributed to the success of center pivots. The large number of manufacturers provided a large sales staff to promote this technology. As the systems became more reliable, the continued demand has stayed high. Today, many surface irrigation systems are being converted to center pivot systems throughout the U.S. (1998 Farm and Ranch Irrigation Survey, http://www.nass.usda.gov/census/census97/fris/fris.htm),

The research community also increased the number of studies for the design, evaluation, maintenance and operation of the center pivot systems. This was probably a factor in increasing the adoption rate. The other factor that has had a strong influence on the center pivot design was the sharp increase in energy costs. Irrigators demanded low pressure systems to decrease pumping costs. Two commercial companies began focusing on application devices that would operate at lower pressures and still give the desired uniformity on a center pivot system. The healthy competition promoted a rapid development of effective low pressure application devices for use on center pivots. Higher quality plastics became available and were used in the manufacture of these low pressure application devices. The newer plastic nozzles actually are less subject to wear than the previously used brass nozzles. The ability for these plastics to resist the damage from sunlight (UV) has extended the life of these devices. Again, it is the available new materials that has contributed to new developments.

The quality plastics also provide the manufacturers of drip irrigation pipe and emitters a material that allowed them to develop more economical and reliable components. Drip irrigation was just being developed for the market in 1970, with increased emphasis on both research and development during the 1970's and 80's. By 1980, microirrigation systems irrigated approximately one percent of the total irrigated area. Today that number is approximately four percent. The number of acres in the Central Great Plains is report 832 acres in the 1998 census. The development of the filter requirements and filter systems contributes to the acceptance and reliability of microirrigation systems. Increased water cost and limited availability are factors that stimulate the adoption of microirrigation systems. The high cost of these systems becomes economical with high valued fruits and vegetable crops. The uniformity can be high and the soil surface evaporation can be minimized with subsurface drip irrigation systems and they are an excellent choice where water supplies are limited.

Irrigation scheduling technology has improved and the total amount of water applied per season has been decreasing. This is in part due to the better performance of pressurized systems. The 1998 Census reports that 1.6, 1.3 and 0.8 ac.ft./ac were used yearly with sprinkler irrigation systems, in Colorado, Kansas and Nebraska, respectively. Surface irrigation systems used yearly totals of 1.6, 1.6, and 1.0 ac.ft./ac in Colorado, Kansas, and Nebraska, respectively. This demonstrates that less water was used where the farmer could more easily control his irrigation system. Applying the right amount of water at the right time is also better understood by irrigators. In the late 1960's, computers became more available and water budget programs were developed. Many of these programs were developed for main frame computers and demonstrated by different government agencies. Now there are many versions of the water budget approach to scheduling that have been developed by researchers and consultants. Private consulting firms provide the service of recommending irrigation schedules with weekly visits to each field. The limited availability of evapotranspiration data was a major hurdle when this technology was first developed. Today most western states have some level of weather station networks and climatic data are readily available from different media sources such as newspapers, telephone, television, satellite networks and the internet.

Irrigation scheduling programs are used by a limited number of growers. This is not because the programs don't work, but most irrigators do not have the time nor inclination to run their computers daily during the irrigation season. Time is valuable and they will invest it where they perceive the most benefit. My experience is that farmers will use irrigation schedules if someone is providing them the results or if the system is automated. Consultants have filled this gap but this is not an expanding market or service. What typically happens is that an irrigator, after contracting with a consultant for several seasons, soon knows what his recommendation will be when the report is given to him. It is an educational process and the irrigator soon questions the value of a continuing contract. Irrigation scheduling technology has

been effectively used for the education and I am confident that most farmers are doing a better job of scheduling irrigations than before the water management programs were demonstrated. A check book approach can be done in a simple manner without a computer and with a fair degree of accuracy.
Computers were an important tool for the advancement of irrigation scheduling technology. But, computers are important for the design and evaluation of irrigation systems. Many models are used for the design of surface, sprinkler and drip irrigation systems. Computers are continually decreasing in cost for the amount of computer power available. Electronic technology is also a key element of many of the controllers used with all types of irrigation systems. Precision agriculture is a new technology that uses global positioning systems (GPS) in addition to computer technology. Geographical Information Systems (GIS) are available for manipulating and processing spatial data. GPS and GIS are used in the design and installation of irrigation systems.

Current government research programs stress the transfer of new technologies. Cooperative Research and Development Agreements (CRADA's) are encouraged between government researchers and industry to facilitate the transfer of new technology.

Water rights issue is of high importance in the Central Great Plains. There is extreme competition for the water between states as well as from municipal and industrial demands for the water. The current drought is a major problem particularly in Colorado. It is uncertain if many irrigators on the South Platte basin will be allowed to pump water in the 2003 season. The matter is in the hands of the Water Courts and the outcome is highly uncertain.

ASAE NATIONAL IRRIGATION SYMPOSIA

Four National Irrigation Symposia were organized and sponsored by ASAE on 10 year intervals beginning in 1970. The first two were cosponsored by the University of Nebraska and held at Lincoln. The later two were cosponsored by the Irrigation Association (IA) and were held in Phoenix, AZ simultaneous with the IA International Irrigation Exposition. Speakers were predicting the opportunities and potential for automation of surface irrigation. However, this did not take place as predicted. As seen in Figure 1, sprinkler systems became much more prominent. Even though the government was promoting furrow irrigation through research and for newly constructed projects, there was not an industry that provided systems. A major problem confronting surface irrigation automation systems is the unique designs needed for individual fields. The fact that a commercial company did not sell complete systems forced the irrigator to buy components and essentially make his own system. Consultants were not readily available to design the efficient automated surface irrigation system. Center pivots were designed for installation and only needed to be adjusted to the field dimensions. Surge irrigation controllers were provided by industry and had some limited success. Surface irrigation has the inherent problem of the variable soil intake that controls the uniformity. Small depths are difficult to apply economically and uniformly. We will continue to have surface irrigation where water is available in sufficient quantities and labor is available. Even though many areas are limited on available water, many areas have sufficient water at a low cost. Thus, these areas have no incentive to improve their irrigation performance.

The technical program for the First National Irrigation Symposium, 1970 were all invited papers which included a broad coverage of all irrigation technologies. Surface drip, subsurface drip and subsurface irrigation was in its infancy in 1970. A number of authors provided research results and discussed the potential value of these new irrigation systems. Most of the progress had been made only in the ten years prior to1970. The problems identified were related to plugging by roots, blockage of openings by solids and sharp differences in uniformity between emitters.

Surface irrigation and auto-mechanized surface irrigation was the area receiving the most attention. It was still recognized as the dominant method of irrigation with 81% of the irrigated area using surface systems. Swarner, (1970) presented a paper on the potential auto-mechanization on the 17 million ha. irrigated with surface irrigation systems. Looking into his crystal ball he saw the irrigation system of the future to be controlled by moisture-sensing devices installed at selected sites in the field to determine when water is needed and how much to apply. Electronic controls activated the valves controlling the water and delivering it in sequence and shut down the system when the optimum moisture levels were restored. The controls would be extended reaching back progressively through the distribution system to open or close farm headgates or gates at the storage reservoir. He hypothesized that we could use either moisture sensing devices or a computer to calculate the consumptive use from solar radiation or some other criteria. He envisioned that a computer could provide the alternative schedules for irrigation and the water user could select the best option. He did predict that the automation could apply to sprinkler and trickle irrigation as readily as to surface irrigation.

Sprinkler irrigation papers were presented on solid set, center pivot and traveling sprinklers. They also included the application of sprinklers for climate modification, application of chemicals, and liquid waste disposal. Pair, (1970) presented a paper entitled "Mechanized Sprinkler Systems—their Applications and Limitations, What Next? He categorized nine basic types of sprinkler systems as 1) handmove portable lateral, 2) tow-line, 3) giant sprinkler, 4) side roll, 5) side move, 6) center-pivot self-propelled continuously moving, 7) straight lateral self-propelled continuously moving, 8) traveler, and 9) solid set. He predicted that only three of the basic systems will remain as we search for the perfect system; 1) handmove portable lateral, 7) straight lateral self-propelled continuously moving, and 9) solid set. His vision was that the handmove system would be used in irregular areas. The lateral move would have the best water distribution pattern under all wind conditions and the solid set would be buried lines with risers and sprinkler heads that would be retractable below the ground level to not interfere with cultural operations. The system would have automatic adjustable nozzle sizes and could be used for frost control, chemical application, environmental control and irrigation. It is interesting to reflect on the actual changes in sprinkler irrigation systems in the past 30 years. Pair reported that sprinklers irrigated about 20% of the total area in 1970 and predicted an increase to at least 80% as water supplies become more critical. Sprinklers are about half way there today, but not with the systems he predicted.

The main thrust of the papers for environmental considerations were to improve irrigation scheduling. Discussions were given on using soil water indicators and plant water indicators for irrigation scheduling. Several papers discussed using of climatic data to estimate evapotranspiration (ET) and calculate water budgets for irrigation scheduling.

Again all papers for the Second National Irrigation Symposium were invited. The number of papers was limited due to the concurrent publication of the ASAE Monograph "Design and Operation of Farm Irrigation Systems." The themes of the major sessions were 1) Advances in Irrigation System Design, 2) Advances in Irrigation Management and 3) Future Needs and Advances in Irrigation. These were preceded by more general speakers, namely Ronald Robie, Director of Water Resources, CA; Nebraska Lt. Governor Roland Leudtke; Robert Young, Economist; Hester McNulty, League of Women Voters; William W. Wood, Jr., Economist and W. R. Z. Willey, Environmental Defense Fund. These first presentations brought a unique perspective to the symposium and challenged the audience at the National Irrigation Symposium to consider a broader perspective.

It was reported that there has been little incentive for any major innovation to improve efficiency of water use in the last century. Most of the development of irrigated agriculture has focused on the development of water delivery subsystems and the almost complete neglect on other problems. A wide gap exists between "hardware development" and the development of all the other requisites for increased agricultural production. A major obstacle to upgrading systems is institutional constraints including water laws. This was particularly true for the Bureau of Reclamation projects and others where the water was directly diverted from the stream or from on line storage reservoirs.

Most of the sprinkler changes were in the development of low-pressure application devices. Drops were introduced for center pivots that work in conjunction with the newer application devices. Big guns were developed with extended radii. Auto connections were developed for use with sideroll, big guns, and linear move systems. Plastic became widely accepted for application devices and for improved flow control and pressure regulator devices.

Surface irrigation dropped from 81% in 1970 to approximately 2/3 of the total irrigated area in 1980 (Figure 1). The automation projections from 1970 had proceeded slower than anticipated in the 10 years. Microprocessors were beginning to be used in the controls of surface irrigation automation systems, particularly for surge irrigation. New trash screens were developed. As with sprinklers, the use of plastics in gated pipe including a flexible pipe was being adopted. Laser leveling had brought about the ability to rapidly and accurately level land for improved surface irrigation. Low energy precision application (LEPA) systems were developed and adopted particularly for areas with limited water. LEPA was included as both a surface and trickle irrigation advance, even though it uses the center pivot and linear move systems for moving the application devices. Increased computer power had made surface irrigation models a viable technique for surface irrigation system design and evaluation.

Trickle irrigation was approaching one percent of the total irrigated area. Major advances were made in light weight pipe, quick connect fittings, emitters and filters. Computer design procedures and guidelines for operation and maintenance were improved. System automation was greatly improved and the application of chemicals was seen as a valuable contribution to the future of trickle irrigation. Systems include subsurface, above ground and mechanically moved.

Emphasis was given to the value of evaluating a system to identify deficiencies in design and system operation. The goal was to have operational levels equal or exceed the design level of performance. Labor, water, energy and hardware were key ingredients for system selection and one must consider the economics to differentiate between success and failure.

The emphasis on management was seen as an area that had become more prominent in the irrigation research and technology activities. Upgrading water delivery schedules require flexible schedules to allow improvement of irrigation water management on the farm. Close coordination between the water supply agency and the farm operators are needed. Improved schedules made possible the automation of on-farm irrigation and permit increased efficiency of surface systems.

Decreased energy costs are important for sustainable irrigation production. Energy for pumping irrigation water can be reduced by reduction of net water application, improved irrigation efficiency, reduction in total dynamic head and improved pumping plant performance. The 1998 Census for the Central Great Plains states reports approximately 47 % of all center pivots are low pressure (<30 psi). Other possible cost savings are from decreased peak electrical demands, reduced nitrogen leaching through more efficient irrigation and incorporation of conservation tillage practices.

Increased accuracy in estimating irrigation water requirements was becoming more important as several western states were experiencing lawsuits or other legal deliberations between water users. It was predicted that future research would include emphasis on refining yield and water consumption relations, refining methods of estimating irrigation water requirements and development of irrigation schemes that minimize energy and water requirements. Significant progress had been made in improving crop coefficients. It was generally understood that an upper bound of yield vs. ET relationship exits. An efficient scheduling process to produce the maximum yield possible with an attainable ET level is usually possible. Since profit frequently maximizes near the maximum yield level; it was suggested that relatively few management regimes are of primary interest. Irrigation in humid areas is particularly important where soils have low water holding capacity and crop rooting depths are limited. Without irrigation, there are extremes in production due to the highly variable distribution of rainfall. Future research was identified as needed to aid in system design, operation, and scheduling technology. The teaching of irrigation scheduling technology through the extension service had increased significantly in the last decade. Commercial irrigation scheduling services were providing improved water management technology to an ever-increasing number of growers.

The last two National Irrigation Symposia were cosponsored by ASAE and the Irrigation Association (IA) and was convened in Phoenix concurrently with the IA International Exposition. The program was significantly different in that the majority of the technical sessions was developed from a call for papers with just a few invited presentations. Many of the typical research results were presented. Water table management using drain lines to both drain and subirrigate were being rapidly accepted in the southeast U.S. Major improvements in drip emitters and the use of slow release herbicides in drip systems were commercially available. A number of papers were presented on the improvements and technology transfer of irrigation scheduling. These included the description of state wide weather networks where data are made readily available to growers for their use in improving their irrigation management of both agricultural crops and turf.

The theme of the fourth keynote session in the Third National Irrigation Symposium was Irrigation and Society. Moore and Downing, (1990) presented two cases demonstrating how cities were buying land for the sole purpose of obtaining water for their urban and municipal use. They saw this type of solution expanding in the southwest. We will probably see more of this approach in the Central Great Plains where water is needed not only for municipal and industrial uses but also for wildlife and environmental needs. Wallace (1990) emphasized the reasons why the development and use of our nation's water resources have become so important and visible a set of policy issues. He indicated that we can find win-win solutions but they will come with significant political battering and strategizing. The answers to the long-run use of this nation's water can be found through conservative political debate and comprise. He concluded that we can find the needed compromises.

The fourth National Irrigation Symposium recognized that future systems will need to put additional emphasis on improved water quality and will come under more scrutiny for preventing non-point pollution. The buzz words of the 70's (water conservation, xeriscape, water reclamation, resource management, water quality and product quality) became serious business in the 80's and became words of wisdom and the price of admission in the 90's.

Lessons from History

We often can learn from history. The preceding review of the history of irrigation and of the four previous decennial National Irrigation Symposia provide us a glimpse of history that we can use to predict the future. A reflection on the history of irrigation shows that much of the new technology has been developed in the last century. If the pace of technology changes continue, we will probably see the same degree of change in the next 50 years that we witnessed in the last 100 years.

Irrigation has been practiced for several thousand years. The cause of most of the systems demise is not clearly known. However, it is postulated that the major problem has been the salinization of the irrigated area. The second probable cause is the lack of available water. It is logical that either could have stopped irrigation. I will limit my scope to the last 100 years and postulate about the causes and forces that have brought us to the current state of irrigation technology. Irrigation systems more than a century old were more than likely surface irrigation with the water diverted directly from the streams. Our current census shows that only 50% of the area is irrigated with surface systems compared to 81% in 1970, (Figure 1).

I should have learned from the predictions made at the earlier ASAE Symposia not to attempt to predict where we are going. However, I will give joy to someone in the future to report how ridiculously wrong I was. First, even though some would stop irrigation completely, I predict irrigation will continue in the future. Current public opinion opposes the policy for expanding irrigation and constructing storage facilities. The federal government has curtailed new projects in the West. Even private or local government is finding it more difficult, if not impossible, to build new irrigation facilities because of environmental impacts and public opinion. Current public sentiment is that we should be dismantling some of the existing structures. The environmental and fish and wildlife groups are strong proponents to leave more water in the stream and to go back to nature. We have seen what can happen in Oregon and California where the water is left in the stream for fish and not made available to the farmers.

We will see a decline in the irrigated area in the West from what it is today. The increased demand for water will reduce the amount for irrigation and more will be used for industrial, domestic and environmental needs. Increased salinity and erosion will remove irrigation in some areas. However, an increase in worldwide demand for food if population doubles by 2050 will require increased irrigated production. In humid areas, I predict more irrigation development. Supplemental water can reduce the risk associated with crop production. Irrigation reduces the drought affects on the year to year variability in production. Water conservation, xeriscape, water reclamation, resource management, water quality and product quality are issues we still face. The recommended strategies to deal with these issues are for increased cooperation, education, technology, planning, implementation, efficiency, and hard work. It is obvious that we must do a better job of educating the public of the issues so that we can solve the problem of ever decreasing water availability.

The types of systems will continue to evolve. My crystal ball is foggy when it comes to predicting a totally new type of system. Subsurface drip irrigation will have the percentage biggest increase in irrigated area. Surface irrigation will continue to decrease and will soon be less than the 50% of the total irrigated area in the U.S. Sprinkler irrigation systems will continue to increase in the near future but I don't believe it will reach the 80% predicted by Pair (1970). As we discussed irrigation technology depends on the current available technologies. Pumping plants, aluminum, plastics, computer technology, laser technology and industry marketing and designing new products and systems are what led to our current technology. The drip industry will continue to develop more effective systems for high value crops and areas with limited water. These systems can be very effective on any size or shape of field.

Moving sprinkler systems (center pivot and linear) have the characteristics to apply variable water and chemicals as precision agriculture becomes adopted. Precision agriculture may offer a similar affect to the adoption of moving systems as did the increase in size of farms, which demanded systems that required less labor. The direction will depend on how the industry meets the challenge to provide a benefit to precision agriculture. The opportunities are here to provide variable applications of water and chemical as an integral part of precision agricultural. Record keeping will be needed for satisfying the regulations controlling the use of chemicals.

There is no doubt the future of irrigation will be integrated into the information age. Precision agriculture is moving in that direction. I see more sophisticated use of computers and controls on new irrigation systems as was predicted in 1970. Sensors will play a big part in this new technology. They will be located in the field and transmit data to control centers. Satellites and aircraft are being promoted for sensor platforms as the way of the future. Being cost competitive and providing immediate access to real time data is a challenge to the remote sensing industry. Irrigation scheduling will become part of a more extensive data collection and processing system. The technology is there but the challenge is to deliver it to the end user in a package that is user friendly and automated with minimum time requirements. Time is a very precious commodity to our farmers.

Environmental concerns will have an increasing impact on the future of irrigation systems. In 1970, environment was used to imply changing the temperature and humidity with irrigation systems. Today environment implies the pollution of our water and soils or reduction of habitat and biological diversity. Runoff from irrigated fields is prohibited in many states and is already changing the management and operation of existing systems. The public is demanding that agriculture not degrade our environment. The challenge is for the industry and producers to preserve or enhance the environment; if not regulations forcing major changes will result. I hope that we have the foresight and willingness to prevent non-point pollution and minimize regulation. Most of us agree that regulations are difficult to write that can be applied universally. Most problems require unique solutions based on local and site specific conditions.

Irrigation is and will be needed to provide the high quality food that we have all learned to enjoy. As the world population continues to grow, we will need to continually increase the production of food and fiber. Irrigation will continue to change not only in the U.S. but in all of the world. The world demand for food is continuing to increase and our productive land is decreasing with the conversion to industry and housing for the increasing populations.

Probably my biggest regret is that I am approaching retirement and will not be an active part of the action in the next 30 years. The challenge is great and I encourage all of you to put your efforts together to solve and be a proactive force and not be reactive and allow major restrictions to unduely limit irrigation in the future. We must form partnerships between industry, researchers and producers to develop tools and technology that are readily acceptable. It isn't always the best technical solutions that are adopted. Reliable products and technology accompanied by the sales network and technical support are important. Research needs to be forward looking but not forget our customer. The forum of the CPIA for discussing research needs and approaches is of extreme value in assuring that our research is solving real problems. Surface irrigation automation was good research but we did not understand the customer needs and partnerships necessary for commercializing the technology. The industry, researchers and producers need to work together to assure that we obtain the best solutions for the future of irrigation. Sustainable and environmentally friendly solutions can be found to assure our customers (the consumer) of high quality and affordable food and fiber.

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HISTORY OF CPIA

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INTRODUCTION

The first Central Plains Irrigation Short Course was held on February 13 and 14 in Colby, Kansas. The idea for the short course was the result of ASAE committee meetings held at the 1988 summer meeting in Rapid City, South Dakota. The Irrigation Group recognized the need to increase our efforts in increasing the knowledge and skills of those involved in irrigation throughout the United States. Following the ASAE summer meeting, an organizing committee from Colorado, Kansas and Nebraska explored the need and possibility of cooperatively sponsoring a technology transfer event focused on irrigation. It would include a time for the researchers to discuss research priorities and that we were all telling the same story. Those involved in the very first planning meeting were Danny Rogers, Israel Broner, Norm Klocke and Dale Heermann. We agreed that a workshop format providing current irrigation technology to producers, consultants, government agency personnel and industry was needed. We also agreed that it would be beneficial to have an equipment exposition in conjunction with the work shop. The organizing committee enlisted the help of many others and we were off and running with the first short course and equipment exposition. We are now participating in the 15th annual event.

INITIAL CHALLENGES

The planning committee from each of the states had cooperative extension responsibilities and were quite accustomed to organizing short courses and work shops. The technical program was easily decided on and the technical expertise was readily available in the three state area. We did make a conscious effort to invite participants from neighboring state Wyoming and included speakers from the High Plains of Texas where similar irrigation problems existed. The effort was made to invite the irrigation industry to exhibit current products at the short course. It is always beneficial to have the latest technology being presented by the industry representatives and explain the application to those in attendance.

The challenge of how to deal with the financial details of the joint short course was beyond that which any one state had experienced. It was agreed early on that it would be advantageous to rotate the short course in a different state each year. Each state was responsible for the collection of registration and exhibitor booth contributions to cover the cost of the short course and proceedings. The proceedings have been a valuable part of the annual meeting for the attendees. It provides a good set of notes for their reference when returning to their home.

The concept of organizing an industry/trade association was soon a topic of discussion by many in attendance at the short course and equipment exposition. Marion Miller, who devoted his life to the improvement and adoption of irrigation technology, volunteered to assist in starting an industry trade association. He had been involved in helping establish other state irrigation association chapters and was one of the first presidents of the national Irrigation Association. He wrote many letters and sent them to as many of the irrigation industry people that he could identify in the three central plains states. His efforts were successful and Articles of Incorporation of Central Plains Irrigation Association, Inc. were signed on September 16, 1992. The Articles of Incorporation were signed by Theodore Tietjen, Jr., Keith V. Jardine, Ronley R. Schultz, Jr., Larry W. Rumburg, David B. Lott, Dale F. Heermann, Theodore G. Johnson, M. Earl Hess, Dan H. Rogers and Roger W. Schulz. Marion was made an honorary charter member. The first president was Ted Tietjen.for the 92- 93 year. The following presidents followed: 93-94 Keith Jardine, 94-95 Ron Schulz, 95-96 David Lott, 96-97 Gary Newton, 97-99 Bill Orendorff, 99-01 Ray Glaser, 01-03 Dwight Scholl.

The business of the CPIA is conducted at two annual meetings of the Board of Directors. Voting rights are reserved for Regular members. Regular membership shall be available to irrigation equipment manufacturers, distributors, dealers and installers, registered engineers and/or engineering firms, companies that design irrigation equipment, and manufacturer representatives. Technical membership is available to individuals employed by local, state or federal governmental agencies. The due structure is set on the basis of membership class. The Board of directors has three representatives from each of the states of Colorado, Kansas and Nebraska. The officers of the board shall be president, vice-president and secretary-treasurer. One technical member from each state serves as an educational advisor.

CENTRAL PLAINS IRRIGATION ASSOCIATION.

The objectives and purposes of the non-profit organization whose principal objective is to enhance agricultural irrigation which shall include:

1. Promoting standards for proper design, installation and management of irrigation systems.
2. Promoting water and soil conservation through the economic use of irrigation practices.
3. Communicating information to farmers and the general public about agricultural irrigation.
4. Encourage cooperation among all segments of the industry
5. Promoting a closer liaison with financing agencies.
6. Promote ethical business practices within the industry
7. Cooperation with agencies or organizations in the efficient use of water.

They have been a strong supporter for the continuation of the Central Plains Irrigation short course and have also cosponsored other meetings. The Association accepted the financial responsibility for underwriting the annual short course and equipment exposition. The Board of directors began discussing establishing scholarships with one going to each of the three states. They have been awarded at the $500 level since 1994. Education has been a primary focus for the CPIA. In 1996, the Board of Directors made the decision to provide more continuity for the association by hiring an executive assistant. Donna Lamm was selected and began serving in that position, April 1996. This has brought more continuity to the Association and monthly Events Calendars are sent by email to the membership. She has been responsible for taking minutes at meetings; doing the bookkeeping; sending out three newsletters a year; making a directory; handling correspondence; answering questions; and helping organize the Short Course and Equipment Exposition.

The CPIA has typically held two meetings per year. One at the time of the annual Short Course and Equipment Exposition and the other during the late spring or summer time frame often in conjunction with the 3I show in Kansas. They are continually evaluating the success of the CPIA activities and questioning if changes should be made. The success and attendance has varied from one meeting site to another and it is always a challenge to do an adequate job of publicity for assuring a good attendance. The most recent discussion has reaffirmed that the technical credits for consultants and government agency personnel are of benefit to the irrigation industry. Discussion of whether to join with some other group in hosting the annual event was explored. The general conclusion was that there is a real benefit to reach a different audience by rotating the meeting sites and the networking with the attendees, many of whom do not attend the larger expositions such as the 3I show in Kansas and the Husker Harvest Days. The short course directly targeted toward irrigation is a needed and valuable program that would potentially suffer if the annual event were cosponsored with another interest group.

SUMMARY OF CPIA CONFERENCES

The first Central Plains Irrigation Conference was held February 13-14, 1989 in Colby, Kansas. This meeting in Colby is the 15th Conference. The typical format has been a series of concurrent technical sessions that are presented multiple times in two days. At a number of the earlier meetings the researchers and interested industry had research discussion to gain an more in depth understanding of the research being conducted in the three states. This was particularly valuable to the many researchers that made presentations and then had the opportunity for more interactive discussion with each other on the latest technology and the research needs. The discussions and interaction with the producers, consultants, industry and government agency personnel provided an immediate agenda for a better understanding of the researchable problems or areas that should be presented in following conferences. The technical sessions are target for the area adjacent to the meeting site.

We have had many opportunities to participate as presenters at the conferences. The interaction with the attendees has provided us with a sense of direction in our own research programs and future presentations. My most memorable experience came at the 1991 conference in North Platte, Nebraska. I was on the program prior to lunch and was certain that I did not want to be long and interrupt the time set for the lunch break. In the middle of my slide presentation with the lights out, suddenly the moderator came up to me at the podium with a question. Are you about finished? I was taken back by his question, but he immediately explained that Governor Kerry had entered the room and asked for the opportunity to make a few comments. He was coming into North Platte for a business meeting and noticed all of the cars at the Holiday Inn. He, like any good politician, decided that he should stop and address a ready made audience. As he had come into the session, he requested just a moment or two to address the group. I suggested to the moderator that I could, given a couple of minutes, quickly complete my presentation. I have always told the organizers that I have never been stopped during a presentation before and in fact not since at any other conference. They had gone to extra effort to have the Governor stop by and shorten my presentation. My question; Is the Governor of Kansas going to come in while I am presenting this interesting story?

The following is the locations and years in which the conference was held in the 15 years of the existence of the Annual conference.

Colby, Kansas	1989,1997, 2003
Garden City, Kansas	1995, 2000
Goodland, Kansas	1992
Burlingtion, Colorado	1996
Lamar, Colorado	2002
Sterling, Colorado	1993,1999
Wray, Colorado	1990
North Platte, Nebraska	1991,1998
Kearney, Nebraska	1994, 2001

Summary of Proceedings

A number of factors ultimately influence the number of papers and topic areas that are published in the conference proceedings. It should be noted that not all presentations are accompanied by a proceedings paper and so no numerical summary of the proceedings papers can exactly summarize all the topics presented over the years. The proceedings papers are a mixture of invited and voluntary papers, and thus reflect a mixture of perceived interests of the conference organizers in that given year and of the topics various speakers may be prepared to present. In general, the conference organizers do consider the needs of the specific location of the meeting. For instance, center pivot sprinkler irrigation topics often predominate in locations where furrow irrigation has rapidly declined. There is also a core block of irrigation scientists, extension specialists and agency staff that are engaged in long term activities related to a particular topic area and it is common for these activities to be reported on.

There have been 236 papers with 1812 pages given at the Central Plains Irrigation Conference during the years 1989-2002 (Table 1). Allowing for overlap between topic areas, there were 265 papers and 1996 pages in 18 distinct topic areas.

As might be expected, the topic areas related to center pivot sprinklers, furrow and surge irrigation and subsurface drip irrigation (SDI) were popular topic areas with 99 papers consuming 781 pages. There was a tendency for furrow irrigation papers to decline somewhat over the years as those acres declined and for SDI papers to increase as the technology for its use in the Great Plains developed (Table 1). Center pivot sprinkler papers were consistently strong over the years and at all locations, reflecting the growth and current predominance of this irrigation system type.

Table 1. Summary of Proceedings from the Central Plains Irrigation Conference, 1989-2002.

Topic area	Proceedings Papers	Total Pages	Proceeding Papers by Period 1989-1993	1994-1998	1999-2002	Proceeding Papers by Location Kansas	Colorado	Nebraska
Center Pivot Management	23	169	15	6	2	10	6	7
Center Pivot Sprinkler Design	23	174	10	9	4	10	4	9
Furrow and Surge Irrigation	26	242	10	12	4	9	3	14
Subsurface Drip Irrigation Mgmt.	17	111	2	8	7	6	8	3
Subsurface Drip Irrigation Design	10	85	0	6	4	3	2	5
Irrigation Scheduling	28	196	12	10	6	9	12	7
Crop Water Use and Soils	12	60	4	8	0	10	2	0
Limited Irrigation	17	151	9	3	5	9	5	3
Water Quality and Nutrient Mgmt.	27	128	10	8	9	10	8	9
Chemigation	7	54	3	4	0	2	3	2
Precision Agriculture and GIS	8	59	0	3	5	1	2	5
Wastewater Applications	7	57	0	0	7	1	3	3
Salinity	4	57	0	0	4	0	4	0
Irrigation Economics	17	166	3	10	4	7	4	6
Irrigation System Conversions	10	88	4	5	1	3	5	2
Pumping Plants and Energy	11	88	4	3	4	3	4	4
Water Policy and Resource Mgmt.	15	85	6	3	6	10	2	3
Safety	3	26	0	2	1	1	2	0
Total	265	1996	92	100	73	104	79	82

Note: Papers listed in multiple categories when distinct topic overlap occurred.

The actual number of papers was 236 and the number of pages was 1812 for the years 1989-2002.

Meeting locations

Colby, Kansas -- 1989, 1997
Garden City, Kansas -- 1995, 2000
Goodland, Kansas -- 1992

Sterling, Colorado -- 1993, 1999
Wray, Colorado -- 1990
Burlington, Colorado -- 1996
Lamar, Colorado -- 2002

North Platte, Nebraska-1991, 1998
Kearney, Nebraska-1994, 2001

Papers dealing with irrigation scheduling, crop water use and limited irrigation have also been very important topic acres throughout the years in all three states with 57 papers and 407 pages. Additionally, this area would clearly overlap with other papers listed in other topic areas such as water quality and nutrient management, economics and the various irrigation system topics.

Water quality and nutrient management, chemigation, precision agriculture and GIS, wastewater applications and the salinity topic areas are often interrelated and this group had 53 papers and 355 pages. This group also had emerging areas of interest (Table 1). Most of the papers related to precision agriculture, wastewater applications and salinity have been presented during the last four years. These topic areas are likely to remain in future conferences as producer interest grows and technologies become more fully developed. The topic of salinity generally was of greater emphasis in locations experiencing current problems (e.g. Arkansas River) but as water resources continue to decline, salinity can become an issue at additional locations. It is good to note that the mutual aspects of good irrigation and water quality management have been consistently recognized and addressed since the earliest conferences.

Irrigation economics, irrigation system conversions, and pumping plants and energy are recurring topics with 38 papers and 342 pages. The amount of emphasis on these topic areas is often tied to the relative economic prosperity in the rural areas. Crop and irrigation management issues often have increased emphasis when the economy is poor and system conversion and pumping plant upgrades are often associated with a better farm economy.

Water laws and policies vary across the three states, but water policy and resource management papers still continue to be of interest to producers. Over the years there were 15 proceeding papers in this topic area with 85 pages published. This topic area is also one which is frequently given in general sessions or at meal functions. Often these speakers are legislators or state agency staff whose schedules often change at the last minute. As a result, many of the water policy presentations are not available in the proceedings.

At the conclusion of this 2003 conference, there is likely to have been about 250 distinct papers and nearly 2000 pages of text in the proceedings from the 15 years of the conference. Some things have changed over the years and some things have remained relatively unchanged. The proceedings continue to be a good source for irrigation system and management information in the Central Great Plains.

CONCLUSION

I want to conclude by saying that the Central Plains Irrigation Conferences have been a great success. It is the dedicated effort of the program committee that includes both industry representation and technical leadership from the three states to arrange for the excellent technical programs. The CPIA deserves a special thanks and recognition for there extra efforts in promoting the educational aspects of the Annual Conference. They also have contributed of their time and resources in participating in the Equipment Exposition. This is a very beneficial part of the annual event. We also are very pleased that they have continued their support of a scholarship program for those studying irrigation science and technology. The Board of Directors has continually evaluated the format, content and location of the annual Conference. I would encourage the Board and CPIA to continually review the goals they set for themselves in their Bylaws. It is the professional dedication of the industry and technical membership that contributes to the excellence of our annual conference. Together we can all make a difference and assure that irrigation is sustainable and limited water supplies are used effectively for production and the enhancement of our natural resource environment.

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SPRINKLER DESIGN & UNIFORMITY CONSIDERATION OVERVIEW

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INTRODUCTION

Irrigation has developed dramatically across the Central Plains during the last half of a century. There were few lands irrigated before the 1950s. Since then the area has developed extensive amounts of land (figure 1). As of the 1997 US Census the amount of irrigated land in several counties in the Central Great Plains exceeded 200,000 acres/county. Many counties in the three state area exceed 100,000 acres/county. The High Plains Aquifer (Ogallala Aquifer) is the primary source of water for most of these lands. In fact, there is little irrigation in areas of the Central Plains when the aquifer is not present.

Today center pivots are the primary source of irrigation in the region. The migration from surface and other forms of sprinkler irrigation has been ongoing for several years and results from several situations. First, mechanized sprinkler irrigation systems require substantially less labor than other methods of irrigation that were previously used. In many cases the availability of labor has constrained producers and pivots were a welcomed development. Pivots also have the potential to be very efficient. This has become more necessary as groundwater supplies have dwindled in some areas and/or regulations have been developed to restrict the amount of water applied to crops or limited the amount of land that could be irrigated.

Since pivots constitute the vast majority of the sprinkler irrigated land in the Central Great Plains this discussion of sprinkler design will focus solely on their design. The design of pivots involves the following steps:

1. Layout the system on the land to be irrigated and gather relevant information about soils, slopes, crops and water supplies.
2. Determine the water supply rate (system capacity) needed to satisfy crop water requirements.
3. Select the type of sprinkler package that will be used, and then determine the size and location of the sprinkler devices to be used on the center pivot.

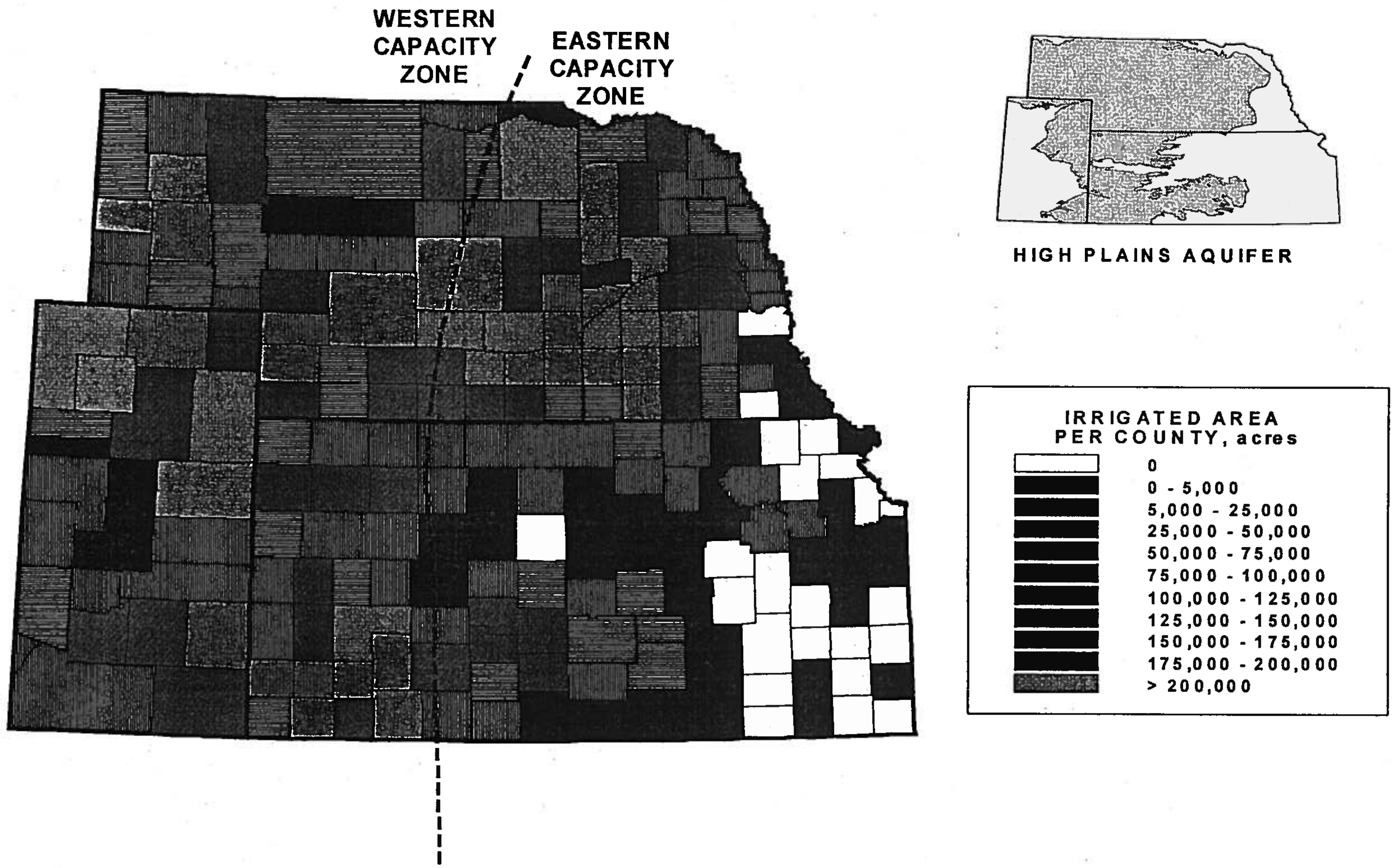

Figure 1. Density of irrigation in counties in the Central Plains States and the alignment with the High Plains Aquifer.

SYSTEM PLANNING AND LAYOUT

The first step in the design of any irrigation systems is the layout of the system for the land that is available. The layout should consider the size of the field, the types of soils in the field, slopes in the field (especially at the outer edges of the field) and any impediments to the rotation of the center pivot lateral. An example is shown in figure 2 for the layout of a pivot where a sizeable portion of the field consists of silt loam soil and other portions of a sandy loam soil. We will see later that these conditions will affect the discharge (gallons per minute, gpm) that will be required and the potential for runoff from the sprinkler packages that are installed on the pivot. The setting in figure 2 contains a farmstead in one corner of the field that will restrict the complete rotation of the pivot. At this point the decision needs to be made regarding the length of the pivot lateral. It would be possible to shorten the lateral so the pivot could make a complete revolution, the pivot point could be moved to the southeast to allow the pivot to make a complete revolution, or the pivot could operate only over a portion of the field in what is often referred to as a windshield wiping pattern. Additionally modifications could possibly be made to the farmstead to allow for complete revolution. Any of these decisions could be correct; however, the decision must be made and the consequences of the layout in the design and operation of the pivot must be considered. Once the operation of the pivot has been determined, the amount of land irrigated with the pivot should be determined. The actual irrigated area is important for water supply and water rights as well as for farm management. The layout should also consist of the location of other important physical features such as the location of the well or other water supply system, location of electrical lines, etc. It is best to develop the layout to a known scale so that the length of pipe, electrical wire and other factors can be determined. Photographs available from the USDA Field Service Office are often an excellent base map for the system layout. If features in the field could interfere with the rotation of the center pivot, i.e., items such as an already installed well, it is desirable to draw the paths of each tower in the field to determine if special lengths of spans will be required for the pivot lateral. Of course actual measurement in the field will be necessary to provide the accuracy needed for final design and installation.

It is essential to consult with the appropriate governmental entity early in the design process to determine the types of permits required before developing water resources. Of course, most of the surface water supplies in the Central Plains have long sense been appropriated and it is very unlikely that additional irrigation development will be possible based on surface water. Limitations on the use of groundwater are also expanding rapidly across portions of the region and each state, and in some cases smaller political divisions such as Natural Resource Districts or Water Conservation Districts, have unique procedures for development of water resources. You should have a clear understanding of these constraints as the design is developed.

SYSTEM CAPACITY

The next step in the design is the determination of the amount of water that should be supplied to the irrigated land. We refer to this quantity of water as the system capacity and it is usually expressed in gallons per minute (gpm) or gallons per minute per acre of irrigated land (gpm/acre). The capacity should be large enough to satisfy crop water requirements during the peak water use periods of the year. However, excessively large capacities can lead to runoff with center pivots and overly large capacities often contribute to poor irrigation water management. The variation of installation cost for a reasonable range of system capacity is usually small and generally cost variations do not play a major role in the design. In many locations in the Central Plains the water supply capacity is limited by the ability of the aquifer to provide water to a well or by the delivery capacity of the surface water purveyor.

The system capacity is based on the types of crops to be grown, the soils

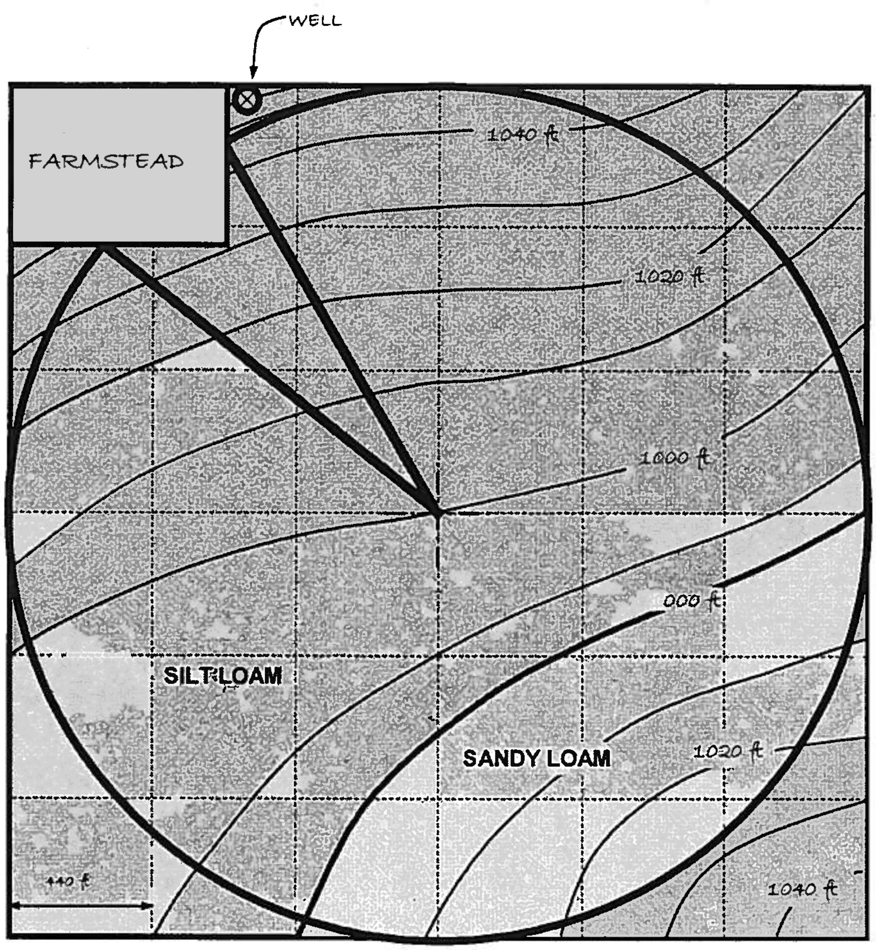

Figure 2. Illustration of a layout map needed for center pivot design.

present in the field, the amount of risk that the irrigator is willing to accept and the anticipated application efficiency of irrigation system. In the Northern Central Plains the primary irrigated crop has traditionally been, and continues to be, corn. Corn generally uses water at near the maximum rate during the middle of the summer and therefore provides a good estimate of the system capacity that would be needed for other crops as well. Guides have been developed for the Northern Central Plains for the required system capacity. The results in figure 3 is based on analysis of a series of years for different soil types (von Bernuth, et al., 1983). The method relies on the allowable depletion of soil water before irrigating. The allowable depletion is computed as:

$$Ad = Rd \times TAW \times MAD \quad \textbf{(1)}$$

where Ad is the allowable depletion in inches, Rd is the root depth in feet, TAW is the total available water holding capacity of the soil (inches/foot) and MAD is the management allowed depletion expressed as a decimal fraction. The total available water holding capacity of the soil is generally determined based on the soil texture. Typical values are given in table 1.

Table 1. Total water holding capacity of soils.

Soil Texture	Total Available Water Holding Capacity (inch/ft.)(TAW)
Loam, and silt loam and very fine sandy loam with silt loam subsoil	2.5
Sandy clay loam, loam, and silt loam and very fine sandy loam with silty clay subsoil	2
Silty clay loam, clay loam, and fine sandy loam	2
Silty clay	1.6
Clay, sandy loam	1.4
Loamy sand	1.1
Fine sands	1

The management allowed depletion is often take as 0.4 to 0.5 and the root depth can usually be estimated to be 4 feet for the actively managed root zone for corn unless there are subsoil impediment to root development.

The net system capacity that is required to maintain soil water content above the allowable depletion is shown in figure 3. The net system capacity is the supply rate that is required if the irrigation system was available to operate at anytime the system is needed and if the irrigation system and manager were able to perfectively apply the water at 100 percent efficiency.

An example will help illustrate the use of figure 3. If corn was to be irrigated in western Nebraska (see figure 1) on a sandy loam soil and the management allowed depletion was specified as 0.5, then allowable depletion would be:

$$Ad = Rd \times TAW \times Rd = 4.0 \times 1.4 \times 0.5 = 2.8 \text{ inches} \qquad \textbf{(2)}$$

Using figure 3, the net system capacity would be approximately 5.3 gpm/acre. Thus, if 125 acres were irrigated the net system supply would have to be approximately 660 gpm. The net system capacity computed in figure 3 represents the amount that would be needed to avoid crop water stress 9 out of 10 years. With this capacity there may be some years, such as 2002, where more capacity would be desirable. However, we generally recommend designing for the 90 % probability.

The net system capacity is adjusted for the fraction of the downtime for the irrigation system and the application efficiency of the system. Downtime, expressed a decimal fraction, is the amount of time that the system is inoperable. Reasons for downtime could be for system maintenance, equipment breakdowns and electrical load management/control. For example, if you have

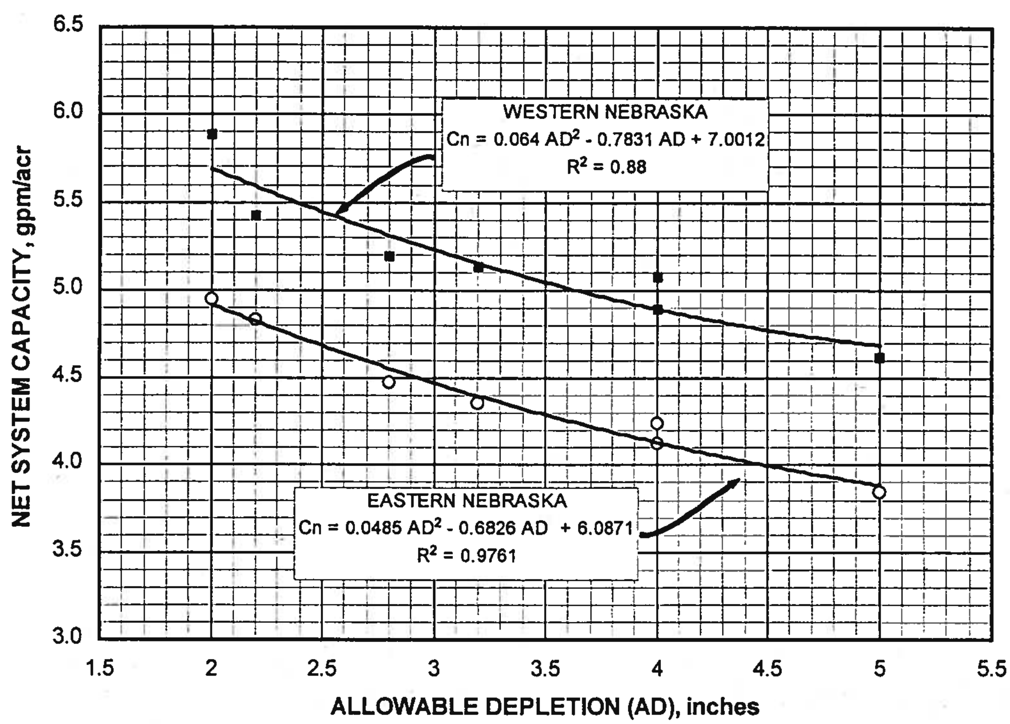

Figure 3. Net system capacity required for center pivots in western and eastern Nebraska.

electrical load management one day per week then the downtime would be 1/7 = 0.14, i.e. 14%.

The application efficiency is used to describe the fraction of the water applied to the field that is stored in the root zone for future crop water use. Water that is applied to the field can evaporate as droplets while in the air, as droplets on the crop canopy or as water that leaves the soil surface and enters the atmosphere (figure 4). A small amount of water from center pivots may drift from the intended point of application and arrive downstream either in the same field or in adjacent tracts. Usually the amount of water that drifts from the field is quite small. Some water that is applied to the field may runoff the intended point of application. Runoff water may actually leave the irrigated field or it may accumulate in low lying areas within the field. When the water accumulates in low spots the excess infiltration at that point may percolate through the root zone and be lost to future crop use. If center pivots are properly designed and managed, the systems can be very efficient. Application efficiencies for center pivots often range from 85% for impact sprinkler packages to values in the 90% range for systems that apply water nearer the surface of the crop. Other manuscripts in the proceedings provide more defendable values for the application efficiency for specific types of sprinkler packages and also discuss the management practices required to achieve the design efficiency.

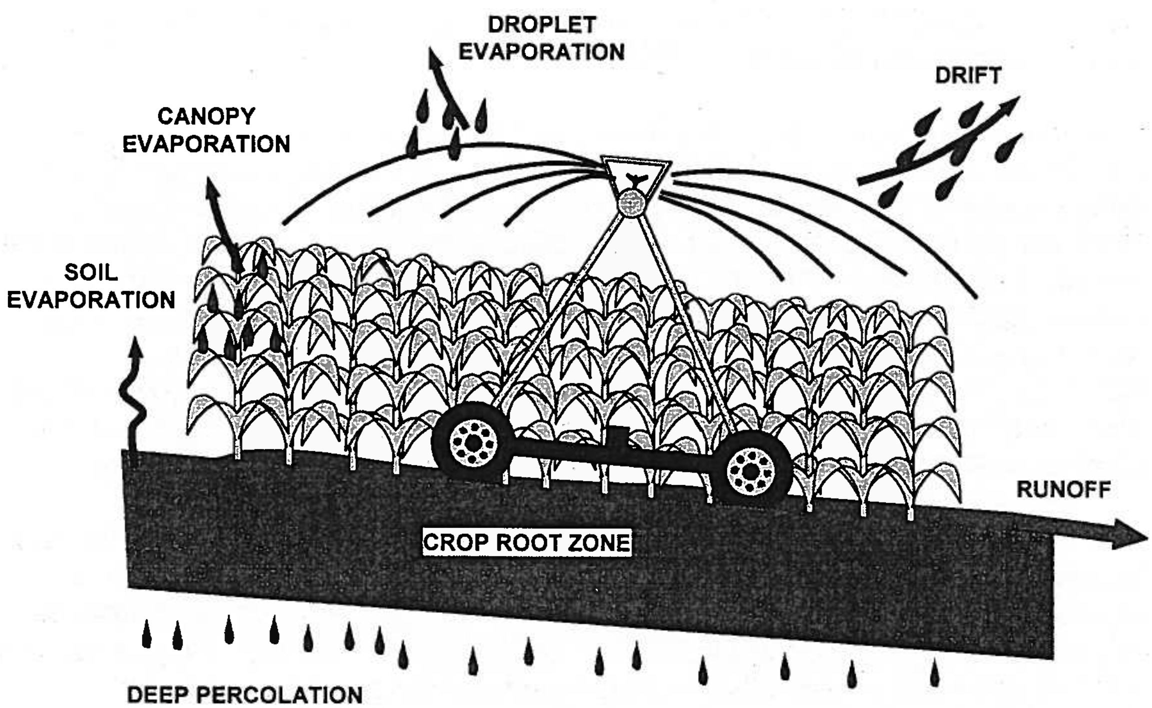

Figure 4. Diagram of processes that affect the application efficiency of center pivot irrigation systems.

The actual, gross, capacity that is required from the water supply must be large enough to overcome losses of water during application and to account for the downtime. The gross system capacity that is required is computed based on:

$$Cg = \frac{Cn}{Ea \times (1-Dt)} \qquad \textbf{(3)}$$

where, Cg is the gross capacity in gpm/acre, Cn is the net system capacity in gpm/acre, Ea is the application efficiency expressed as a decimal fraction (i.e., between 0 and 1) and Dt is the downtime expressed as a decimal fraction.

For example, if an application efficiency of 85% was used and there was one day of downtime per week the gross system capacity for the previous example would be:

$$Cg = \frac{Cn}{Ea\,(1-Dt)} = \frac{5.3\text{gpm / acre}}{0.85\,(1.0-0.14)} = 7.25\text{gpm / acre} \qquad \textbf{(4)}$$

When the gross capacity is used with the 125 acre field that was used in the previous example we see that a system flow rate of approximately 900 gpm would be required. If the procedure was repeated for a silt loam soil the capacity would need to be about 800 gpm to maintain soil water levels above the allowable depletion 90% of the time when one day per week is lost to downtime and the application efficiency is 85%.

The results shown in figure 3 are based on analysis of results for Nebraska conditions. Heermann, et al. (1974) conducted a similar study using a slightly different way to compute the probability of exceeding the allowable depletion. Their results were based on climatic conditions for Akron, Colorado. While there are slight differences in the resulting curves, the results for western Nebraska can be used for eastern Colorado. The results would be expected to be to apply for Northwest Kansas as conditions are similar to Central and Western Nebraska. The procedures for the system capacity methods presented here are also described in the NebGuide by Kranz, et al. (1989). The NebGuide can be located on the internet at http://www.ianr.unl.edu/pubs/irrigation/g932.htm.

The capacities determined in this procedure are ideal and unfortunately at many locations in the Central Plains the aquifer is not good enough to provide the capacity calculated in this procedure. In those cases the irrigator must choose among several undesirable alternatives. One choice is to accept a higher level of risk that soil water levels will drop below the targeted allowable depletion. Perhaps the capacity that is available will only meet the requirements in 8 of 10 years rather than the design probability of 90%. The irrigator may choose to avoid load management programs that would cause the system to be off 14% of the time. Ultimately, the irrigator may be faced with accepting either suppressed crop yields in some years and/or reducing the amount of land irrigated. The irrigator may also choose a crop rotation that will shift the peak water use period of part of the field to allow the pivot to meet each peak use on a portion of the field. In almost all cases the irrigator will want to adopt an irrigation strategy that will develop and maintain a full soil profile just prior to the peak use periods of the year. Selection among these alternatives depends on individual choices and producer conditions and it is not possible to provide a general recommendation.

It has been our experience that excess capacity often leads to inefficient irrigation. With center pivots this occurs in two ways. First, if the capacity is much larger than the crop water requirements then the machine needs to be idle for a period of the weak. However, if the irrigator does not adopt effective irrigation scheduling methods the temptation is to "let the pivot run". This leads to excessive applications and often leaching of nitrate-nitrogen. The second problem with excessive capacity is that the application rate with center pivots increases directly with the system capacity and the potential for runoff is larger for high system capacities.

A range of system capacities is generally feasible. I selected a range between a lower limit of approximately 4 gpm/acre and an upper limit of about 8.5 gpm/acre. The system capacity expressed in gpm/acre can be converted to the equivalent daily water supply rate by multiplying by 0.053. The range of system capacities that fall within this recommended range are shown in table 2. The table does not consider the application efficiency and is simply a comparison of the total supply per unit area per day. The values in table 2 should be multiplied by the application efficiency (as a decimal fraction) to convert the supply rates in table 2 to the amount of water that crops could use as evapotranspiration on a daily basis. For example if the producer had a supply of 650 gpm and irrigated 130 acres, then the supply rate would be 0.27 inches/day. If the application efficiency was 90%, this supply rate would be able to meet a daily crop water use of 0.24 inches/day. This water use rate would be exceeded during the peak water use periods of most years and the irrigator would want to have built soil water storage ahead of the peak to mitigate against stress in the peak water use period. In very dry years when rain does not augment the irrigation supply, such as 2002, it is likely that some stress would have occurred even if the crop root zone was full in late June.

I need to stress that building soil water storage ahead of the peak water use period that occurs from the middle of July through the middle of August is generally recommended if the water supply is limiting. I do not recommend "preseason" irrigation that would apply water ahead of planting. Research has shown that these early season applications are usually inefficient. Instead, irrigators may want to replenish depleted soil water to some extent at the end of the previous growing season, while leaving ample room to store spring rains. Then, the soil water reservoir can be replenished in late May and June when the rainfall picture is more clear. Rain will build the reservoir during wet springs and if

Table 2. Depth of water applied per day (inches/day) for combinations of water supply rate and area irrigated. Multiply these gross values by the decimal fraction of the application efficiency to determine the equivalent rate of evapotranspiration that can be sustained.

Water Supply Rate (Q), gpm	Irrigated Area (A), acres												
	80	90	100	110	120	130	140	150	160	180	200	220	240
300	0.20	0.18	0.16	0.14	0.13	0.12	0.11	0.11	0.10	0.09	0.08	0.07	0.07
350	0.23	0.21	0.19	0.17	0.15	0.14	0.13	0.12	0.12	0.10	0.09	0.08	0.08
400	0.27	0.24	0.21	0.19	0.18	0.16	0.15	0.14	0.13	0.12	0.11	0.10	0.09
450	0.30	0.27	0.24	0.22	0.20	0.18	0.17	0.16	0.15	0.13	0.12	0.11	0.10
500	0.33	0.29	0.27	0.24	0.22	0.20	0.19	0.18	0.17	0.15	0.13	0.12	0.11
550	0.36	0.32	0.29	0.27	0.24	0.22	0.21	0.19	0.18	0.16	0.15	0.13	0.12
600	0.40	0.35	0.32	0.29	0.27	0.24	0.23	0.21	0.20	0.18	0.16	0.14	0.13
650	0.43	0.38	0.34	0.31	0.29	0.27	0.25	0.23	0.22	0.19	0.17	0.16	0.14
700	0.46	0.41	0.37	0.34	0.31	0.29	0.27	0.25	0.23	0.21	0.19	0.17	0.15
750	0.50	0.44	0.40	0.36	0.33	0.31	0.28	0.27	0.25	0.22	0.20	0.18	0.17
800	0.53	0.47	0.42	0.39	0.35	0.33	0.30	0.28	0.27	0.24	0.21	0.19	0.18
850	0.56	0.50	0.45	0.41	0.38	0.35	0.32	0.30	0.28	0.25	0.23	0.20	0.19
900	0.60	0.53	0.48	0.43	0.40	0.37	0.34	0.32	0.30	0.27	0.24	0.22	0.20
950	0.63	0.56	0.50	0.46	0.42	0.39	0.36	0.34	0.31	0.28	0.25	0.23	0.21
1000	0.66	0.59	0.53	0.48	0.44	0.41	0.38	0.35	0.33	0.29	0.27	0.24	0.22
1050	0.70	0.62	0.56	0.51	0.46	0.43	0.40	0.37	0.35	0.31	0.28	0.25	0.23
1100	0.73	0.65	0.58	0.53	0.49	0.45	0.42	0.39	0.36	0.32	0.29	0.27	0.24
1150	0.76	0.68	0.61	0.55	0.51	0.47	0.44	0.41	0.38	0.34	0.30	0.28	0.25
1200	0.80	0.71	0.64	0.58	0.53	0.49	0.45	0.42	0.40	0.35	0.32	0.29	0.27
1300	0.86	0.77	0.69	0.63	0.57	0.53	0.49	0.46	0.43	0.38	0.34	0.31	0.29
1400	0.93	0.82	0.74	0.67	0.62	0.57	0.53	0.49	0.46	0.41	0.37	0.34	0.31
1500	0.99	0.88	0.80	0.72	0.66	0.61	0.57	0.53	0.50	0.44	0.40	0.36	0.33
1600	1.06	0.94	0.85	0.77	0.71	0.65	0.61	0.57	0.53	0.47	0.42	0.39	0.35
1700	1.13	1.00	0.90	0.82	0.75	0.69	0.64	0.60	0.56	0.50	0.45	0.41	0.38
1800	1.19	1.06	0.95	0.87	0.80	0.73	0.68	0.64	0.60	0.53	0.48	0.43	0.40

Inches/day = 0.053 GPM / Acres

it is dry then the pivot can be used during the early part of the season when supply exceeds crop demands. This process needs to be initiated early enough to build soil water supplies while dovetailing irrigations will farming operations.

DESIGN OF SPRINKLER PACKAGES

After completion of the system layout and selection of the system capacity, the sprinkler package can be selected for the center pivot. The system layout will provide information for the length of the entire pivot pipeline and the length of each individual span of the pivot. The layout will also provide the total irrigated area and the soil types that are used in selection of the system capacity.

The design of the sprinkler package involves:

- Selection of the type of sprinklers to use (i.e., the sprinkler package) which will also include specification of the nominal operating pressure and the spacing of sprinklers along the pivot pipeline (called the lateral).
- Calculation of the flow rate, or discharge, needed at each sprinkler along the pivot pipeline.
- Determination of the proper nozzle size for each sprinkler.

The selection fo the type of sprinkler package to install involves consideration of the application efficiency, operating costs and installation costs. The sprinkler package affects the amount of water that could potentially run off of the intended point of water application, the amount of water that evaporates in the air or on soil and plant surfaces and to a small degree the amount of drift lost from the field. Other papers in the proceedings focus on the expected efficiency and costs of alternative sprinkler package designs.

Figure 5 shows that the area irrigated by a sprinkler located at the midpoint of the center pivot lateral irrigates less area that a sprinkler located near the end of the lateral. Since more area is irrigated during the same amount of time, the sprinkler near the end of the lateral requires more discharge than the sprinkler closer to the pivot base. The discharge required from a sprinkler depends on the total capacity of the center pivot, the size of the irrigated field (effective radius of the system), the distance from the pivot base to the sprinkler and the spacing between individual sprinklers along the pivot lateral:

$$q = Cg \times R \times S / 6933 \qquad \textbf{(5)}$$

where q is the discharge in gpm for a sprinkler located at a distance of R feet from the pivot base when the gross system capacity is Cg (gpm/acre) and the sprinkler is spaced at a distance of S (feet) from the upstream and downstream sprinklers. For example, if the system capacity was 6 gpm/acre and the sprinkler outlet was located 1300 feet from the pivot base and the spacing of sprinklers was 9 feet, the discharge required for the sprinkler would be 10.1 gpm. Calculations for all sprinklers along the lateral are usually determined with computer programs developed by sprinkler or center pivot manufacturers or suppliers.

If an endgun will be installed on the pivot to pickup some irrigated area, the capacity of the endgun must be determined. The required flow rate from the endgun can be determined from figure 6. Figure 6 shows that the amount of land area irrigated with and endgun reaches a plateau when the radius of the area irrigated with the endgun is about 15% of the length of the pivot lateral. In fact it is difficult to find endguns that throw water this length. A common length of the endgun radius relative to the length of the pivot lateral is about 10% to 12%. In this case the discharge required from the endgun will be about 20% to 25% of the flow rate for the main center pivot system when the endgun is off. For example, if the total flow when the endgun is off is 600 gpm and the radius of the endgun to the pivot lateral is 10%, then the endgun will require about 120 gpm. This is a major quantity of flow and should be considered when the center pivot is matched to the irrigation pump.

After the discharge for sprinklers on the lateral and the discharge from the endgun are determined the pressure distribution along the lateral is computed. With this calculation the pressure at each sprinkler outlet is computed. The effects of pressure regulators are also computed. These computations provide the pressure available at the sprinkler. The pressure is used to determine the size of nozzle required for the respective sprinkler. These computations are very laborious and are done with computer programs. As a result of the computations, the nozzle sizes for each sprinkler outlet are determined.

Installers must be careful to install the proper sprinkler and nozzle at the right location along the pivot lateral. Unfortunately, we still see cases where installation errors results in putting the wrong sprinkler and nozzle at the wrong location along the lateral. The irrigator should insist on a printout of the sprinkler location and nozzle size chart. The irrigator should at least spot check the installation. With the color coding of newer sprinkler nozzles it is fairly easy to walk along the system and compare the design specifications to what was installed.

This description of the design of the sprinkler package shows that once the type of sprinkler package has been selected, the irrigator's job is generally complete. The computation of the spacing of sprinklers, nozzle sizes, pressure regulation, etc. is generally accomplished by sprinkler or pivot manufacturers and/or suppliers. **It is strongly recommended that producers allow these entities develop the specifications for the design and that irrigators follow manufacturer recommendations**. Manufacturers invest large amounts of resources in developing and testing products. They know what their products can

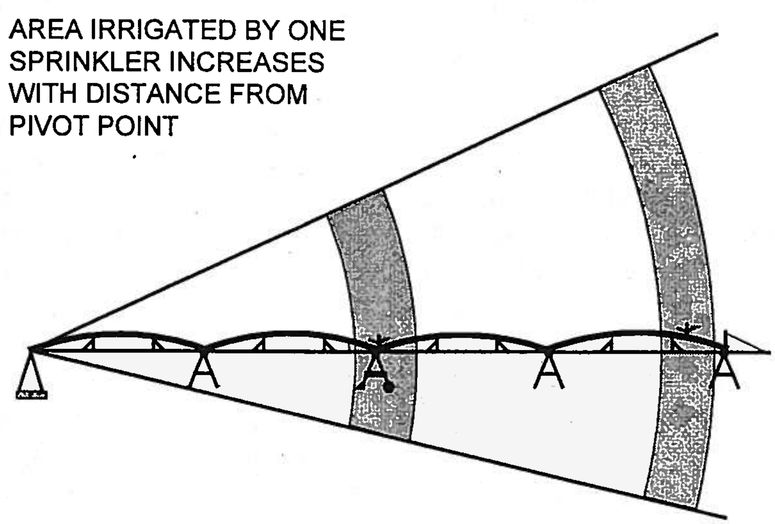

Figure 5. Diagram of area irrigated by a sprinkler located halfway along the pivot lateral and a sprinkler located near the end of the lateral.

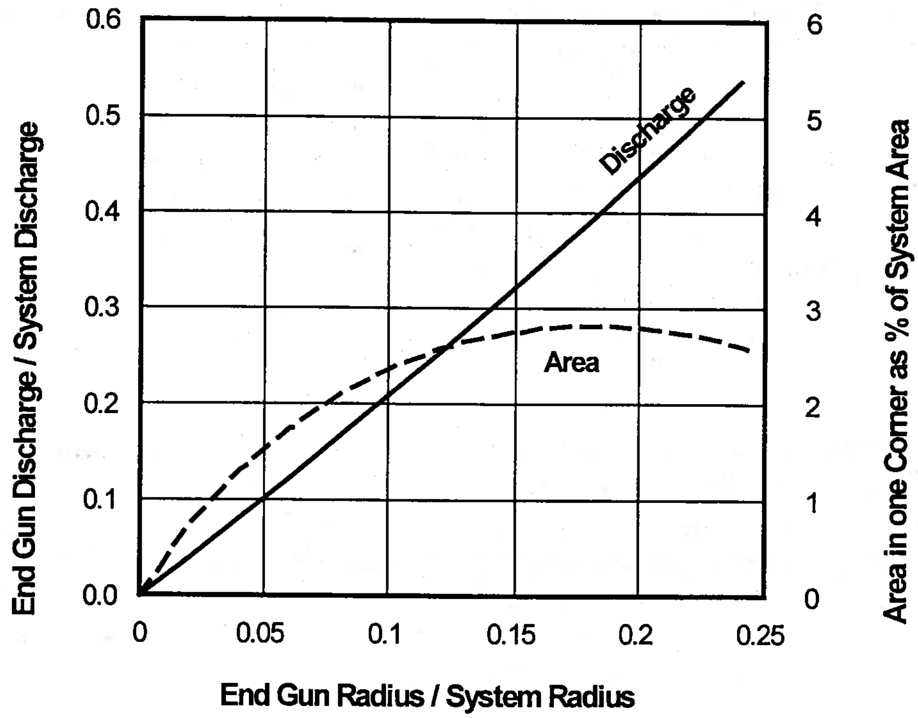

Figure 6. Relationship of the radius of the area irrigated with an endgun to the area irrigated and the discharge required from the endgun.

do and have developed recommendations of how their products should be used.

How do irrigators or dealers modify manufacturers' recommendations? The main variations that occur involve the spacing of devices along the pivot lateral and the height above the ground that devices are installed. Assuming that the discharge from individual sprinklers is correctly computed from the sprinkler supplier or pivot manufacturer, the variations of sprinkler height and spacing primary affect the uniformity of water application.

IRRIGATION UNIFORMITY

Sprinkler irrigation systems are designed to apply water so that plants have equal access to water. It is not possible to perfectly achieve this goal, but center pivots can be designed to very uniformly apply the desired application. The key to achieving the desired uniformity is to provide the adequate overlap of water application patterns between successive sprinklers. The overlap of sprinkler patterns is illustrated in figure 7. The top portion of the diagram shows that about four or five sprinklers along a pivot lateral apply some water to a point on the ground. This pattern is more typical of impact sprinklers and rotating pad sprinklers that have large wetted radii. Sprinklers with stationary spray pad devices may result in fewer sprinklers applying water at a point; however, there still must be adequate overlapping of adjacent sprinkler patterns to achieve uniformity. The only time that overlapping of sprinkler patterns is not needed is when the sprinkler devices are placed close enough together so that equal plant access to water is ensured. This generally occurs with sprinkler packages for low energy precise application (LEPA) system and sprinkler packages that placed in the crop canopy. In each case the spacing of sprinklers along the lateral must be small enough to ensure uniformity. This results in more expensive installation costs. Some growers or dealers try to stretch the spacing to minimize expenses. This generally results in reduced uniformity which reduces application efficiency or crop yield.

Why is overlap necessary? Sprinklers apply water in a circular pattern and the depth of water applied varies along a radial line from the center of the sprinkler to the edge of the wetted radius. The distribution of water along this radial line is referred to as the single-leg distribution of water. Some examples of single-leg distributions for different types of sprinklers are shown in figure 8. The triangular and elliptical patterns are often found with impact sprinklers and the patterns with one or two peaks are common of rotating pad sprinkler devices.

To determine the uniformity of application these single-leg distributions must be overlapped for upstream and downstream sprinklers. This procedure requires accurate information from the sprinkler manufacturers on the distribution of water for their devices at different pressures, nozzle sizes and heights above the soil-crop surface. Computer programs are available to compute the uniformity of distribution. Manufacturers have also measured the performance of their equipment. Either of these processes can be used to develop a sprinkler design that provides acceptable uniformity. It is very unlikely that acceptable uniformity can be achieved without such analyses. Growers and dealers should always stay within the design specifications developed by the sprinkler and center pivot manufacturers.

The height of the sprinkler device above the soil-crop surface also affects the uniformity because water is not thrown as far when sprinklers are close to the surface (figure 9). This reduces overlap and may require closer spacing of sprinklers. When sprinklers are placed in the crop canopy the wetted radius is reduced considerably and the uniformity will be greatly reduced unless devices are placed closer together. In many cases devices should be spaced at a distance that is twice the row spacing of the crops.

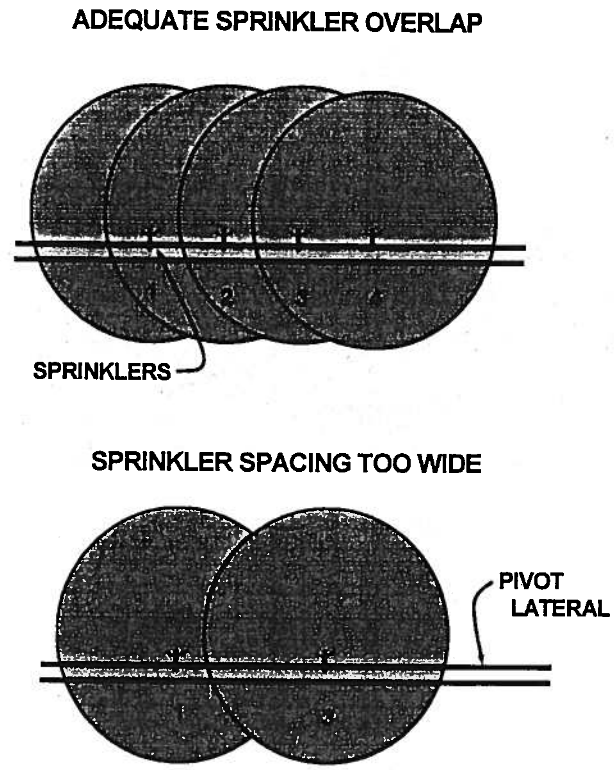

Figure 7. Illustration of the proper amount of overlap with sprinklers and how the patterns would look with inadequate overlapping of adjacent sprinklers.

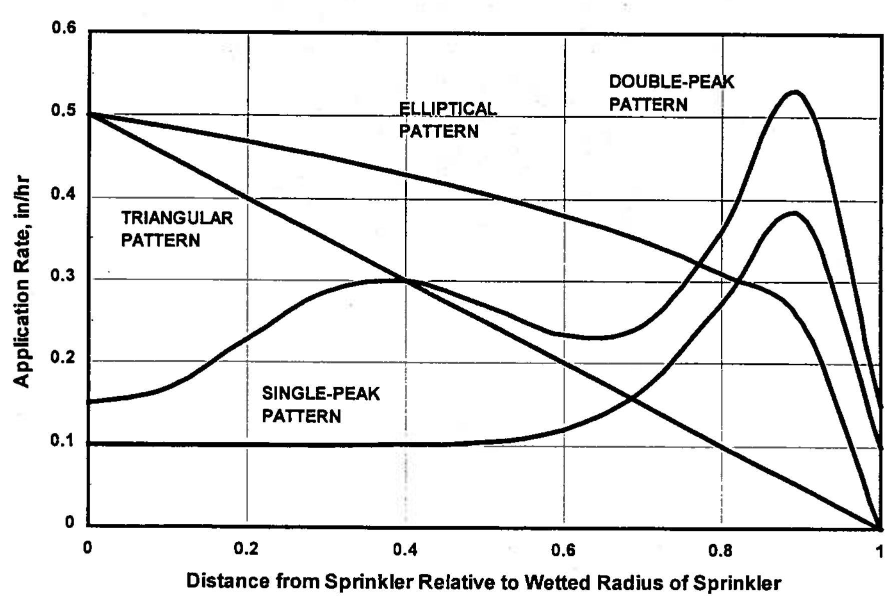

Figure 8. Single-leg distributions commonly found for individual sprinklers.

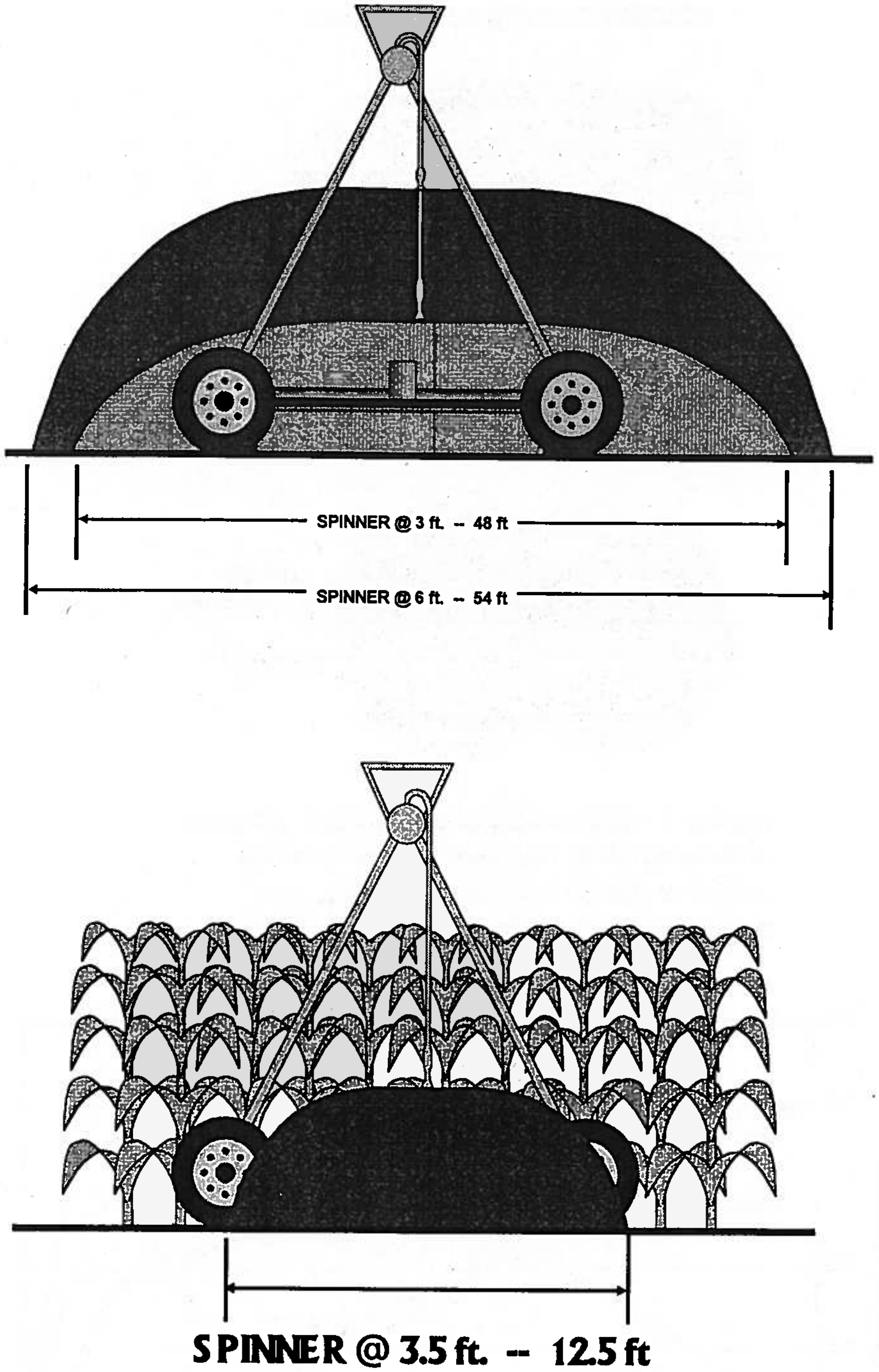

Figure 9. Illustration of the effect of height of nozzle placement and placement in the crop canopy on the wetted radius of a rotating pad sprinkler device.

SUMMARY

This paper presents general considerations for the design of center pivot irrigation systems. Other papers in the proceedings provide details about many of the topics discussed here. The design of a sprinkler system involves the layout of the system on the proposed tract of land, determination of the system capacity required to meet crops water requirements while considering downtime and application inefficiency, and computation of the discharge required for sprinklers along the center pivot lateral. Several decisions must be made during the process. The effect of these decisions on the uniformity of water application and ultimately the efficiency of application should be considered. Center pivots have the ability to apply water very efficiently; however, to attain this potential it is necessary to adhere to manufacturer's guidelines and to combine good design with effective irrigation scheduling and management.

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WATER LOSS COMPARISON OF SPRINKLER PACKAGES

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INTRODUCTION

Sprinkler packages that are available and used in the Great Plains of the United States are widely varied from older impact heads to more modern spray heads or various rotator designs and have an assortment of application and/or placement modes. This paper will mainly address common sprinkler packages in use on center pivot sprinklers and linear (lateral move) machines. Sprinkler packages are designed and selected (purchased) for a variety of reasons. Often high irrigation uniformity and application efficiency are cited as priority goals in selecting a particular sprinkler package or sprinkler application method. In practice, many sprinkler packages can achieve the desired design and operational goals equally well at or near the same costs. Management, maintenance, and even installation factors can be as important as the selection of a package or application method.

This paper discusses the desired traits of various sprinkler packages and sprinkler application modes and discusses the anticipated water losses that might impact both irrigation uniformity and efficiency. In most cases "generic" descriptions are used rather than individual commercial names of sprinkler manufacturers. End-gun effects are not discussed or addressed to a significant degree.

TYPES OF SPRINKLER PACKAGES

Sprinkler Spacing

The first sprinklers used on center pivots were impact heads adopted from hand-move, portable sprinkler lines that had a large angle (~23 degrees from horizontal) of discharge to maximize the water jet trajectory. Many of these were single nozzle types, but some used double nozzles to improve the uniformity for the pattern. Early center pivot design sprinkler spacing was about 32 ft (9.8 m) with impact sprinklers while some later designs used a variable spacing (closer towards the outer end of the pivot). Two principal design modes were commonly used for these packages – 1) constant (uniform) spacing with variable nozzle diameters along the center pivot to vary the sprinkler discharge or 2) almost constant nozzle discharge and head selection with variable spacing (e.g., farther apart near the pivot point and closer together on the outer lengths of the pivot). It was common to mount larger sprinklers on the ends of the pivot (end guns) to cover more land area with a fixed pivot length. A third design mode – called the semiuniform spacing (Allen et al., 2000) is a combination of these two other design modes. The variable spacing mode is easier to apply to rotator-spinner-spray heads but greatly complicates the center pivot pipeline design and the sprinkler package installation and maintenance. These spacing types are illustrated in Fig. 1.

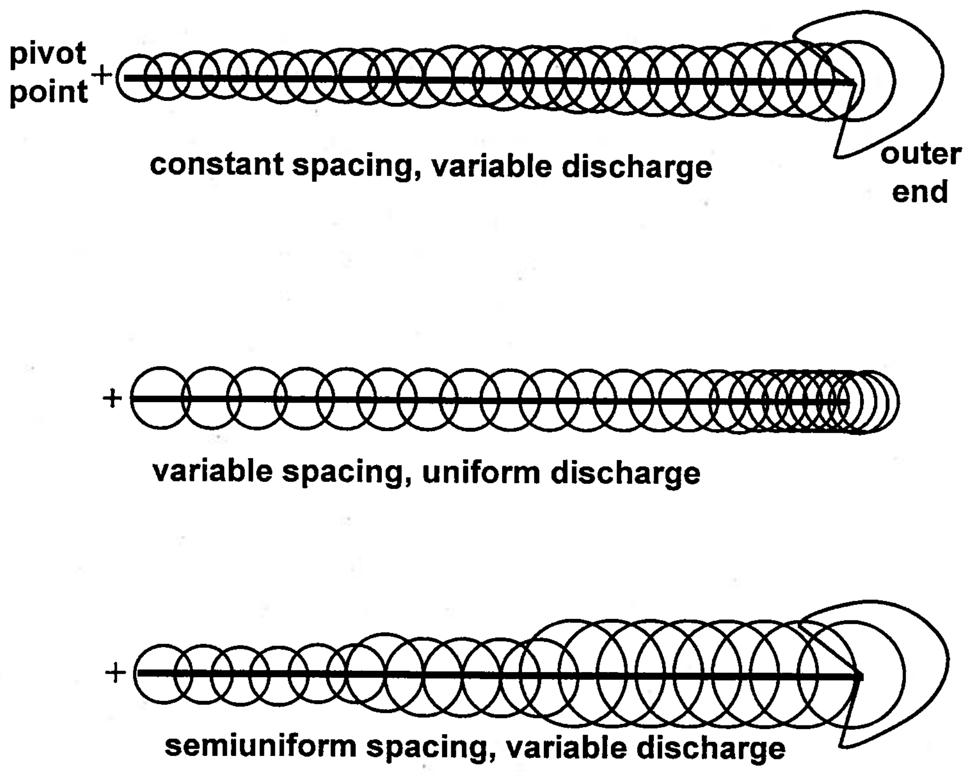

Figure 1. Diagram of typical sprinkler spacing and discharge designs. Modified and adopted from Allen et al. (2000).

The constant outlet spacing is quite common, particularly for closely spaced systems (~5 ft or 1.5 m) used with LEPA (low energy, precision application), LESA (low elevation, spray application), or LPIC (low pressure, in-canopy) methods of application. The sprinkler outlet spacing for non LEPA/LESA type systems with the constant spacing are often spaced up to 10 ft (3 m) apart. This spacing type is still used for pipeline mounted low angle impact sprinklers or spray heads on drops (typically mounted just below the truss rods). One concern with this spacing design can be the larger sprinkler discharge rate at the outer end requiring large nozzles with larger droplets. It can result in the requirement for higher operating pressures in some cases. These two factors — larger nozzles and higher operating pressures — can cause infiltration problems due to soil crusting and/or runoff difficulties from the high instantaneous application rates.

When LEPA and LESA are not used, the semiuniform spacing can rather conveniently be used with a 10 ft (3 m) outlet spacing uniformly along the pivot pipeline. Allen et al. (2000) suggested that the first third of the pivot length might use a 40 ft (12 m) sprinkler spacing, the middle third might use a 20 ft (6 m) sprinkler spacing, and the outer third might use a 10 ft (3 m) sprinkler spacing with the unused outlets plugged. This concept would also work with a 5 ft (1.5 m) outlet sprinkler spacing along the pipeline that might offer conversion options to LEPA, LESA, or LPIC application methods. This semiuniform spacing mode avoids many of the problems with larger nozzles.

The application uniformity will depend on many factors of the design and several operational factors (e.g., wind speed, pivot alignment and the wind direction, topography (tilt of the sprinkler axis in relation to the ground slope), effect on pressure at the outlet, etc., soil type, etc.) The main sprinkler factors affecting uniformity are the sprinkler spacing, the sprinkler device type –its diameter of throw, application pattern type, operating pressure, nozzle and spray plate design, the elevation of the application device above the ground, and any crop canopy interference.

Sprinkler Types

Center pivot sprinklers can be classified generally into two broad types –impact sprinklers and spray heads. Within the impact type, nozzle angles can vary from the older type heads with higher trajectory angles (~23 degrees) to lower angle impact sprinklers (~6-15 degrees) that are typically mounted on top of the center pivot pipeline. Impact sprinklers are usually constructed using brass or plastic materials. They operate with a spring and heavy jet deflector arm with each arm return (from the spring) imparting a momentum to rotate the nozzle jet slightly. It might take up to 100 or more deflector arm returns to cause the impact sprinkler head to make a full rotation. The rotation speed depends on several design factors of the deflector arm; its mass and the bearing in which the sprinkler rotates. Nozzles can be simple "straight bore" types (that operate according to basic orifice principles where discharge depends on the nozzle diameter and the operating pressure) or various design types that provide flow controls by compensating the nozzle discharge –pressure relationship to provide a more constant discharge independent of the operating pressure. The operating pressure of most impact sprinklers is in the range of 25 to 40 psi (170 to 280 kPa), but the operating pressure is higher for larger sized nozzles. Impact sprinklers typically have a 3/4 in. NPT male end (18 mm), but some larger nozzles may require a 1 in. NPT (25 mm) size to reduce pressure losses across the pipeline mounting coupling.

Impact sprinklers have an advantage because they typically have a large radius of "throw", thereby having a larger wetted area and smaller instantaneous application rate (equivalent to the "precipitation" intensity) that can nearly match the soil infiltration rate with fewer runoff and erosion difficulties. Because they must rely on the hydrodynamics of the water jet and its breakup for the irrigation application, transport mechanism, they are affected to a greater degree by winds and subject to greater pattern distortions because of their higher application elevation above the ground or crop. Also, they might have a higher pumping cost due to their greater operating pressure.

Spray heads are a much more diverse classification. They can range from simple nozzles and deflector plates to more sophisticated designs involving moving plates that slowly rotate or types with spinning plates to designs that use an oscillating plate with various droplet discharge angles and trajectories. The rotator types are similar to small, low angle impacts sprinklers, except the sprinkler rotation is controlled by the nozzle jet with a hydraulic "motor." Most spray heads have a near 360 degree coverage and can have deflector plates designed with differing groove sizes to affect the spray streams (deeper grooves with fewer jets to have larger diameter streams in windier cases, shallower grooves with more streams to have smaller droplets, or flat to have a greater droplet diameter range), and they can have streams that are ejected almost horizontal (flat), upward (concave) or downward (convex) with downward orientated spray heads. They can be designed with plates that direct water streams upward at various angles for chemigation of tall or short crops. Spray heads can have partial coverage (i.e., not a complete 360 degree pattern), which are often used near towers to minimize track wetting. Spray heads can be mounted upward on the center pivot pipeline itself. On some linear (lateral move) machines, truss manifolds with three to five spray heads may extend the wetting pattern to achieve a lower instantaneous application rate. Typically, spray heads are mounted on "drops" from "goose-neck" fittings that make a 180-degree bend from the upper side of the center pivot pipeline and longer "goose-necks" may be used to allow matching LEPA or LESA drops to the rows. The drops are usually flexible hoses. For longer drops (LEPA, LESA, or LPIC), the drop hose will typically have a weight (1-2 lb or 1/2 to 1 kg) to minimize swaying from the wind. Usually, the "goose-necks" and drops are installed on alternating sides of the center pivot pipeline. Figure 2 illustrates a typical LESA system with its drops.

Spray heads typically operate at pressures from 10 to 30 psi (70 to 200 kPa), but some LEPA or LESA systems operate at pressures as low as 6 psi (40 kPa). Lower pressure systems or ones with significant elevation changes are usually equipped with pressure regulators to achieve higher uniformities. Spray heads are often constructed from plastic, and the various parts are color-coded (varies by manufacturer).

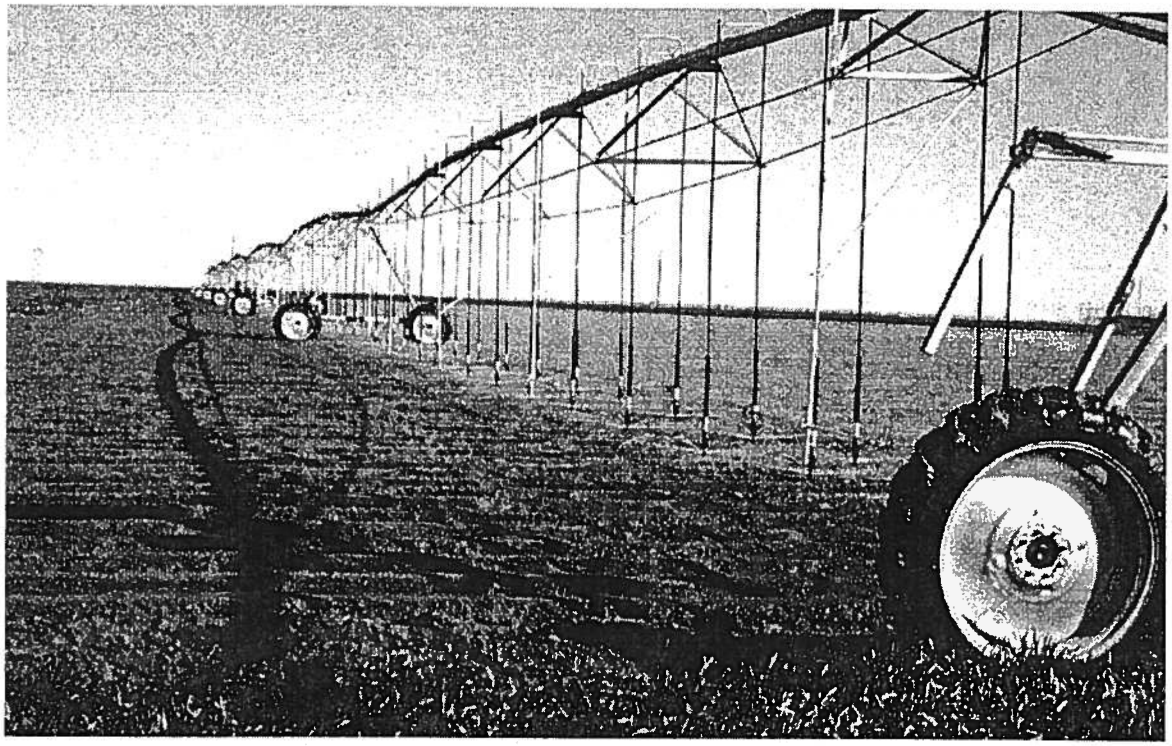

Figure 2. Typical example of a LESA system with spray heads on drops spaced 5 ft (1.5 m) apart).

Allen et al. (2000) describes many of the common types of spray heads from several manufacturers and their characteristics. Table 1 provides a summary of some of the typical sprinkler heads used on center pivots. The list of advantages and disadvantages is intended solely as a guide, and individual situations may have unique situations not characterized here. Readers are encouraged to seek local advice from technical advisors (e.g., county extension agents, USDA-NRCS specialists, irrigation dealers, irrigation extension specialists, consultants, etc.) before making any sprinkler design selection or changes. Figure 3 illustrates the relative application rates under various sprinkler types after (King and Kincaid (1997). The values in Fig. 3 are conceptual. The peak application rate linearly increases along the center pivot radius and is maximum at the outer end. The X-axis presented as a distance scale in Fig. 3 can be converted to a time scale based on the speed of the center pivot at that point (e.g., divide the distance wetted by the speed (ft/hr) to achieve the time course of the application as the pivot passes a particular point). The area under each of the transformed curves will be a constant along the center pivot's length representing the application amount (in. or mm).

Table 1. Characteristics of common center pivot sprinkle types.

Sprinkler Type	Pressure Range psi (kPa)	Typical Height ft (m)	Advantages	Disadvantages
Impact, high angle	25-50 (170-300)	6-15 (1.8-4.5)	Low application rate.	High energy requirement. Exposure to wind effects.
Impact, low angle	25-35 (170-250)	6-15 (1.8-4.5)	Low application rate.	High energy requirement. Still impacted by winds.
360°Spray head, Rotator, Spinner; high location	10-30 (70-200)	6-15 (1.8-4.5)	Lower energy requirement. Closer spacing.	High application rate. Only over canopy chemigation.
360°Spray head, low location LESA or LPIC	10-30 (70-200)	1-6 (0.3-1.8)	Lower energy requirement. Less wind effect. Close spacing. Some have LEPA drag hose adapters. Under canopy chemigation.	High application rate.
Low Drift and Multiplate Spray Heads	10-30 (70-200)	Varied Pipeline Truss Level. LPIC	Lower energy requirement. Lower drift and wind effects. Many configurations. Some have LEPA drag hose adapters and chemigation plates.	High application rate.
Rotator	15-50 (100-300)	Varied. Pipeline. Truss Level. LPIC	Larger wetted diameter, lower application rate. Good resistance to wind effects.	Can have higher energy requirement. Limited in-canopy chemigation applications.

Table 1 (Continued). Characteristics of common center pivot sprinkle types.

Sprinkler Type	Pressure Range psi (kPa)	Typical Height ft (m)	Advantages	Disadvantages
Spinners	10-20 (70-150)	Varied. See Rotators	Low energy requirement. Gentler droplet applications.	Limited in-canopy chemigation applications.
Oscillating/Rotating Spray Plates	10-20 (70-150)	3-6 (0.9-1.8)	Low energy requirement. Low misting from small droplets. Low application rate and gentler applications.	Limited in-canopy chemigation applications.
LEPA Bubble	6-10 (40-70)	1-3 (0.3-0.9)	Low energy requirement. Usually, alternate furrow applications and less evaporation. Multi purpose (convertible from spray to bubble to drag sock). Excellent in-canopy chemigation options.	Extremely high application rate. Requires furrow dikes or surface storage (~1-2 in., 15-50 mm of water volume).
LEPA Drag Sock	6-10 (40-70)	0 (0)	See LEPA Bubble. Less erosion of furrow dikes.	See LEPA Bubble.

Sprinkler Application Modes

The application modes for center pivot "sprinkler packages" can be described as either 1) overhead or over-canopy methods or 2) near-canopy or in-canopy methods. The sprinkler type selected is influenced by the mode of the desired application method. The mode and sprinkler type may influence the required spacing. So these are not independent alternatives. Hence, they have been called "sprinkler packages" because all aspects of design, installation, maintenance, and management affect the "package" performance.

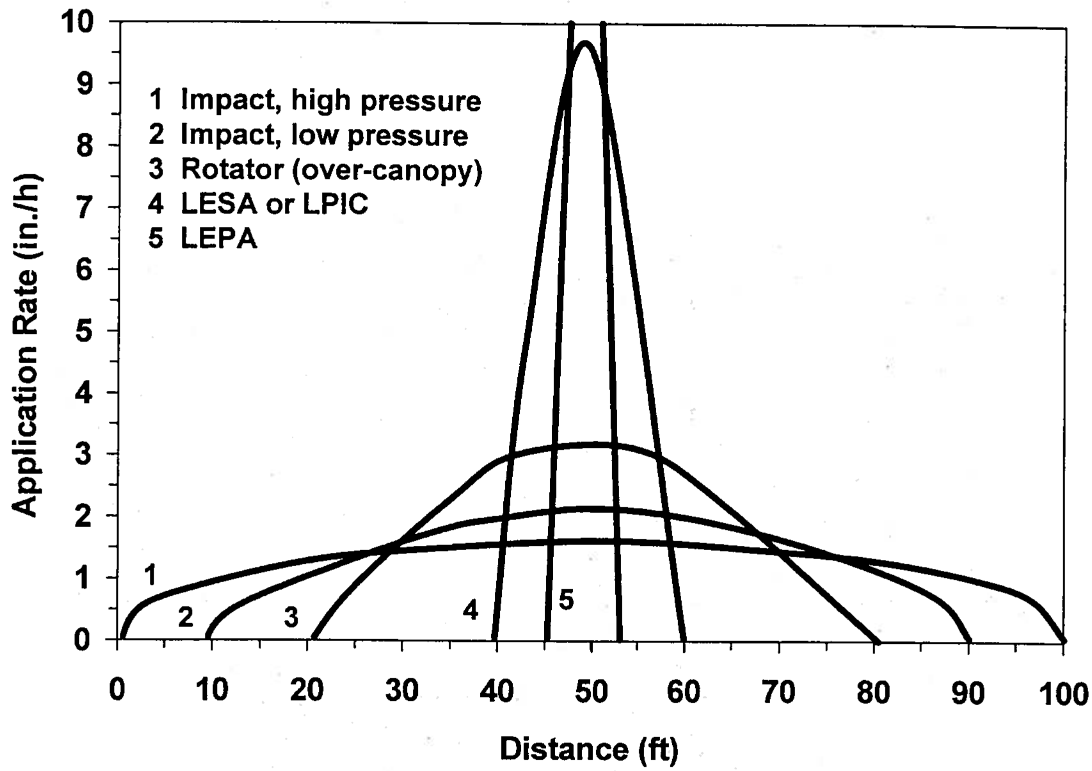

Figure 3. Illustration of the relative application rates for various sprinkler types under a center pivot. Modified and adopted from King and Kincaid (1997). The LEPA application rate is difficult to show because it is essentially a "point" discharge, and its peak was illustrated to exceed the rate range of this graph.

The overhead or over-canopy methods are those application types mounted on the center pivot pipeline itself or those mounted on drops that are typically just below the truss rod elevation above ground. Of course these descriptions are still arbitrary depending on the system height and the crop height. One of the main decision factors for this mode is whether only overhead or over-canopy chemigation is desired or if no chemigation option is desired. Impact sprinklers, spray heads, and rotators are typically considered for this application mode. This mode and application method is well suited to rolling topography, low intake soil types, and crops tolerant of overhead wetting.

The near- canopy or in-canopy application methods are always mounted on drop tubes from the center pivot pipeline. The main difference is whether the sprinkler devices are mounted near the ground (LEPA or LESA), within the crop canopy or the mature crop canopy (LPIC), or just above the maximum height of the crop. Of course, a LPIC system designed for a tall crop may not be a LPIC system in a shorter crop (e.g., a corn LPIC system will not be a LPIC system in cotton, peanut, or soybean crops; Fig. 4). For that reason, we (USDA-ARS Bushland) have preferred to use the names — LESA for a system with the spray heads

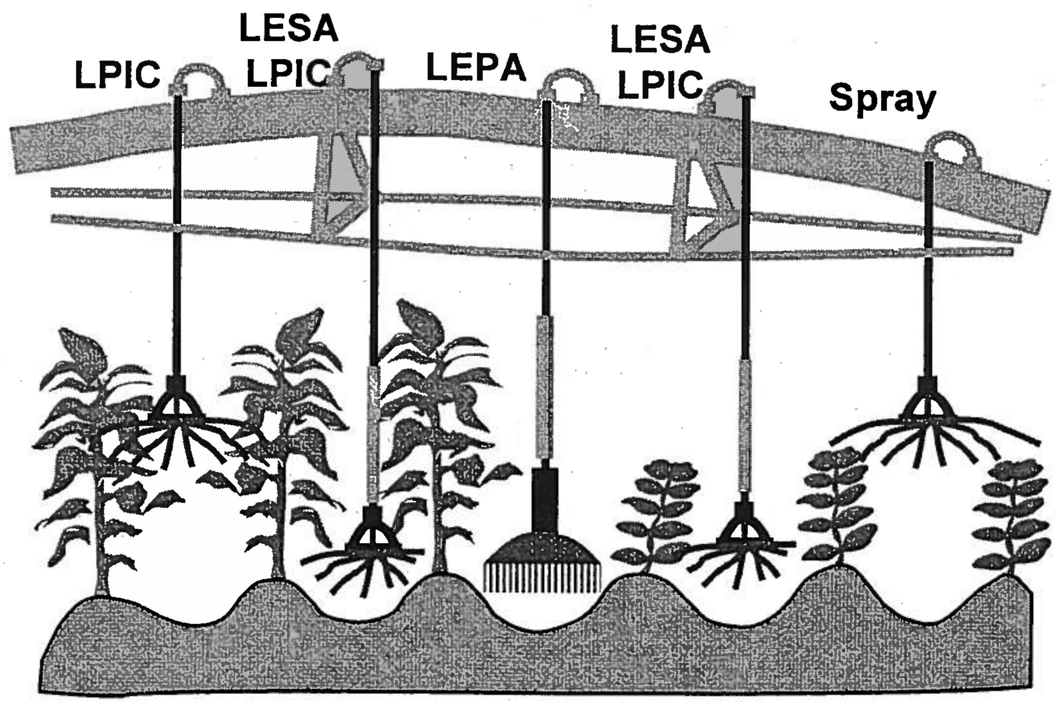

Figure 4. Illustration of the LEPA, LESA, LPIC, and spray application concepts in tall and short crops. The illustration has drops in each furrow to conserve space while actual systems typically use drops in alternate furrows either 60-in. or 80-in. (1.5-m or 2-m) apart depending on the crop row spacing.

mounted 1-2 ft (0.3-0.6 m) above the ground or MESA (mid elevation spray application) for a system with spray heads mounted 5-8 ft (1.5-2.4 m) above the ground. The name LEPA should only be used for a system with bubblers (e.g., an adjustable multi-purpose head) or drag socks mounted on a flexible hose. LEPA hoses can be attached with commercial adapters to many types of spray heads whether the spray heads are mounted low near the ground like LESA or at a higher elevation like a LPIC or MESA system. Although Lyle and Bordovsky

(1981) originally used LEPA in every furrow, subsequent research (Lyle and Bordovsky, 1983) demonstrated the superiority for alternate furrow LEPA. The reasons aren't always evident, but they may result from the deeper irrigation penetration (twice the volume of water per unit wetted area compared with every furrow LEPA), possible improved crop rooting and deeper nutrient uptake, and less surface water evaporation (~30-40% of the soil is wetted). LEPA and LESA work best with either LEPA heads or 360° spray heads. These systems (LEPA or LESA) also have flexibility to chemigate either a tall crop (e.g., corn) or shorter crops (e.g., soybean, wheat, cotton, or peanut). LPIC and MESA systems have the conversion potential to LEPA, but they don't have the under canopy chemigation potential of LEPA or LESA systems. LEPA and LESA systems are typically located in or above alternate furrows or between alternate rows if furrows are not used. LEPA requires a furrow with furrow dikes according to the concepts described by Lyle and Bordovsky (1981) while LESA can be effective without furrows in no-till or conservation till systems. This doesn't imply LEPA heads cannot be used without furrow dikes, but it shouldn't be described as "LEPA". LPIC or MESA systems are typically spaced for a desired uniformity and may not be bound by the row spacing. LPIC systems may require a narrower spacing to compensate for crop interference (Spurgeon et al., 1995).

Lyle and Bordovsky (1981) developed the LEPA concept as a "system" comprising irrigation combined with furrow diking (basin tillage). In fact, all advanced center pivot sprinkler application packages need to be incorporated into a complete agronomic package involving tillage, controlled traffic, residue management, fertility, harvesting, etc. (Fig. 5). Table 2 summarizes several of the typical center pivot "sprinkler packages" and their "system" components.

WATER LOSS COMPARISONS

The efficiency of an irrigation application depends on many factors. The water losses depend on the application technology and operation and include other agronomic cultural aspects. The interpretation and characterization of water loss estimates or measurements involves the conservation of mass applied to sprinkler irrigation as outlined by Kraus (1966). He presented the components as

$$Q_s = Q_{ae} + Q_{ad} + Q_{fi} + Q_{gi} \qquad \text{...[1]}$$

where Q_s is the sprinkler discharge, Q_{ae} is the droplet evaporation during travel from the nozzle to the target surface, Q_{ad} is the water drift outside the target area, Q_{fi} is the intercepted water on the foliage, and Q_{gi} is the water reaching or intercepting the ground. The units for these components can be expressed on a rate, mass, or volume basis. Q_{fi} represents the sum of water evaporated from the foliage during the irrigation (Q_{fe}) and the amount of water remaining on the

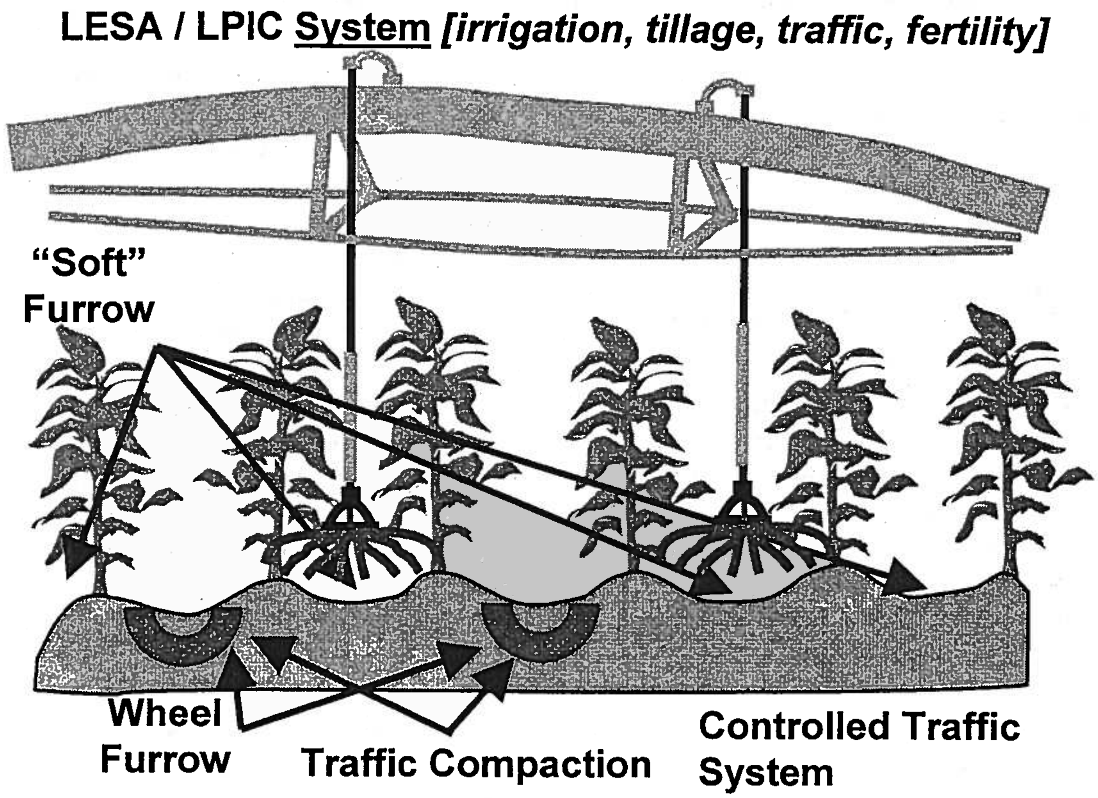

Figure 5. Illustration of the "agronomic system" concept involving irrigation, controlled tillage, fertility, etc.

foliage at the end of then irrigation (Q_{fs}). The water reaching the ground (a defined unit area) can be partitioned into its components characterized as

$$Q_{gi} = Q_{si} + Q_{ge} + Q_{gs} + Q_{gwe} + Q_{gri} + Q_{gro} \qquad ...[2]$$

where Q_{si} is the infiltrated water, Q_{ge} is the water evaporated from the ground during the irrigation, Q_{gs} is the water stored on the ground during the irrigation, Q_{gwe} is the water evaporated from the water stored on the ground prior to infiltration during irrigation, Q_{gri} is the water that runs onto the unit area, and Q_{gro} is the water that runs off the unit area. In its simplest case, irrigation application efficiency is the ratio Q_{si}/Q_s because percolation beneath the root zone can usually be ignored. Percolation beneath the root zone depends on irrigation scheduling and other water management issues. Percolation can be significant in low lying areas in the field that accumulate runoff from upland areas.

Generally for a center pivot, drift outside the area is small and is often ignored; however, it could be more significant with systems equipped with end guns or in

Table 2. Example sprinkler packages with desired tillage and agronomic systems.

Sprinkler Package	Tillage System	Agronomic System
Overhead		
Impact Sprinklers Rotators, Spinners	Any	Any
MESA or Spray	Any. Controlled traffic desired. Basin tillage with ridge-till, reservoir tillage with or without beds. No-till, ridge-till, or conservation till compatible.	Any
Within canopy		
LPIC 360° Spray head Low drift head Spinner Oscillating plate	Any. Controlled traffic desired. Basin tillage with ridge-till, reservoir tillage with or without beds. No-till, ridge-till, or conservation till compatible.	Any
LESA 360° Spray head Low drift head Spinner	Any. Controlled traffic desired. Basin tillage with ridge-till, reservoir tillage with or without beds. No-till, ridge-till, or conservation till compatible.	Any, circular rows desired
LEPA (bubble)	Controlled traffic desired. Basin tillage with ridge-till, reservoir tillage with beds.	Circular rows
LEPA (drag socks)	Controlled traffic desired. Basin tillage with ridge-till, reservoir tillage with beds. (basin tillage is more effective)	Circular rows

extremely high wind situations. Typically, irrigation application efficiency can only be measured after the water application has been completed and perhaps several hours after the irrigation (perhaps a day later). Dynamic measurement of these various components is practically impossible, and their "static" measurement remains complex in most cases unless major simplifications are used. Sprinkler applications usually involve water transport through the air and the integral vapor transfer of water vapor into the atmosphere through the evaporative process affect the Q_{ae}, Q_{fe}, and Q_{ge} components. For methods that wet the foliage, transpiration will decline, and generally the "net" evaporation (evaporative loss offset by the reduced transpiration) is the component of interest. Also, the movement of the water vapor downwind humidifies the drier air reducing the crop evapotranspiration rates, even before the area is wetted by the irrigation. In addition evaporation continues after the completion of the irrigation event from the foliage intercepted water (Q_{fi}) and surface storage water (Q_{gs}) and the evaporation from the ground during the irrigation (Q_{ge}) and following the event (Q_e, total evaporation of water from the ground surface). At the typical observation time, the intercepted water on the foliage and the ground will already have evaporated and these amounts are largely unknown, except by some inference methods (qualitative comparisons; e.g., estimating Q_{ge} from evaporation from an "open" water body near the site). Table 3 outlines the possible water loss components common for various sprinkler packages.

Table 3. Water loss components associated with various sprinkler packages.

	Sprinkler Package			
Water Loss Component	**Overhead**	**MESA or Spray**	**LESA LPIC**	**LEPA**
Droplet evaporation	Yes	Yes	Yes	No
Droplet drift	Yes	Yes	No	No
Canopy evaporation	Yes	Yes	Yes, (not major)	No, (chemigation mode only)
Impounded water evaporation	No	Yes	Yes	Yes, (major)
Wetted soil evaporation	Yes	Yes	Yes	Yes, (limited)
Surface water movement	No, (but possible)	Yes, (not major)	Yes	Yes, (not major)
Runoff	No, (but possible)	Yes	Yes	Yes, (not major unless surface storage is not used)
Percolation	No	No	No	No

Howell et al. (1991) reviewed many of the studies that had measured evaporative losses from sprinkler systems, especially those using lysimeters. They noted the great difficulty in making measurements of evaporative losses, but they found major differences in the application losses for differing sprinkler methods – low angle impacts, LEPA, and over canopy spray (MESA or LPIC) due to their different wetted times, differing wetted surfaces (e.g., LEPA only wetted a small portion of the soil surface with minimal or no canopy wetting). Tolk et al. (1995), using measured corn transpiration, found net canopy evaporation of intercepted water was 5.1 to 7.9% of applied water for a one-inch (25-mm) application volume. McLean et al. (2000) reviewed several past evaporation studies and evaluated above canopy evaporation losses from center pivots using the change in electrical conductivity of sprinkler catch water as an indicator of evaporation. They reported impact and spray losses from –1 to 3%. The negative losses were attributed to atmospheric condensation on the droplets due to the cool groundwater temperatures that were less than the atmospheric dew point temperature. Schneider (2000) reviewed the evaporation losses from LEPA and spray systems (LESA, LPIC, and MESA types). He summarized the limited studies reporting "net" canopy evaporation that had values ranging from 2 to 10% (some of these were simulated and/or based on a theoretical model). Evaporation from LEPA systems ranged from 1 to 7% of the applied amounts with application efficiencies ranging from 93 to 100%. His review of evaporation losses from spray irrigation studies had values that ranged from 1 to 10%, while their mean application efficiencies ranged from 85 to 100%.

Surface water redistribution (runoff from one area to a lower area but not perhaps leading to runoff leaving the field) and field runoff should not occur in most cases. Yet, they regularly happen and affect the infiltration uniformity, deep percolation, and ultimately the efficiency of the application. Spray systems (LESA, LPIC, or MESA) or LEPA systems (despite the use of surface tillage designed to enhance surface water storage volume) are most prone to runoff problems. Soil type and slope play a central role in the surface water redistribution and runoff potential of a particular site in addition to the sprinkler package and system capacity (system flow rate per unit area) (Fig. 6). Either surface storage (basin or reservoir tillage) or crop residues from no-till or profile modification tillage (chiseling, para-till, etc.) may be needed to reduce or eliminate surface water redistribution and runoff. Increasing the system speed (decrease the application depth) generally reduces the potential runoff volume. Both water redistribution and field runoff occur from rainfall that can further impact irrigation water requirements. Few studies are published on rainfall runoff from sprinkler-irrigated fields or that have measured the total season water balance components.

Schneider (2000) reviewed many of the previous studies on irrigation runoff and surface storage as influenced by tillage systems for LEPA and spray application methods. Runoff or water redistribution without basin or reservoir tillage ranged from 3 to over 50% in several studies with the greatest runoff losses occurring from LEPA modes without basin tillage (most in the bubble mode). LEPA applications in alternate furrows will require twice the storage volume needed for equivalent LESA or LPIC systems (representing full wetting like rain or MESA). Runoff from LESA or LPIC systems may be critical on steeper slopes (>1-2%), low intake soils (heavier textures like clay loams), and higher capacity systems (>6 gpm/ac or 0.32 in./d or 8.1 mm/d).

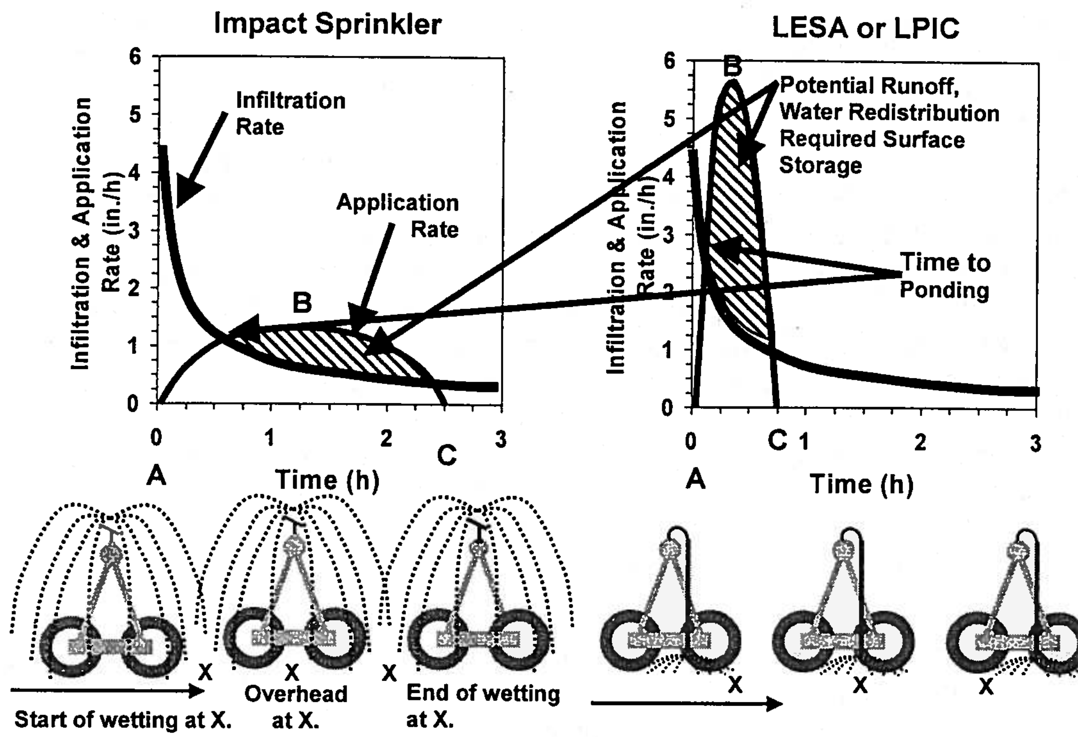

Figure. 6. Illustration of runoff or surface water redistribution potential for impact sprinkler and spray (LESA or LPIC) center application packages for an example soil. (A) represents the start of the irrigation, (B) is the peak application rate (usually when the system is directly overhead), and (C) 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.

CONCLUSIONS

The sprinkler package is a combination of the sprinkler applicator, the application mode, and the applicator spacing. The system capacity determines the peak application rate of the particular sprinkler application package. The sprinkler package should be designed together with the tillage and agronomic system. The particular soil and slope conditions will define the infiltration rate. The intersection area between the infiltration curve and the application rate curve illustrates the "potential" runoff or surface water redistribution that might require surface storage from basin or reservoir tillage needed to reduce or eliminate runoff from LESA, LESA, or LPIC systems.

The type of sprinkler applicator and the mode of application determine the particular components of water losses. "Net" canopy evaporation may be in the 5-10% range. Overall evaporation losses in several cases were between 10-20%. Irrigation efficiency of LEPA systems without runoff were in the 93 -99% range, but without basin tillage LEPA systems in several cases had large runoff (or surface water redistribution) amounts. LESA or LPIC systems can be efficient with evaporative losses less than 10% in most cases, particularly with basin or reservoir tillage or with a no-till system.

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Matching the Nozzle Package to the Operating Conditions

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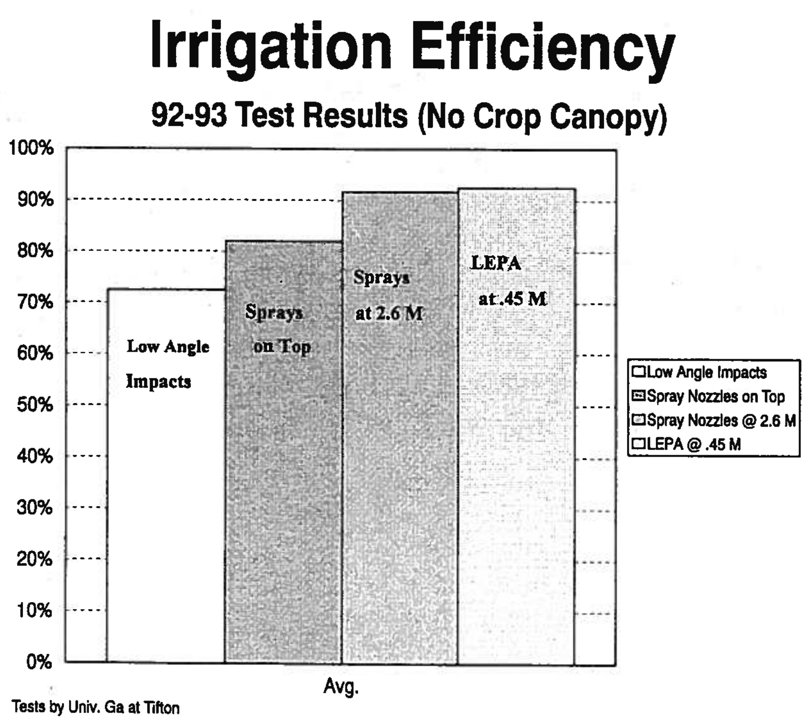
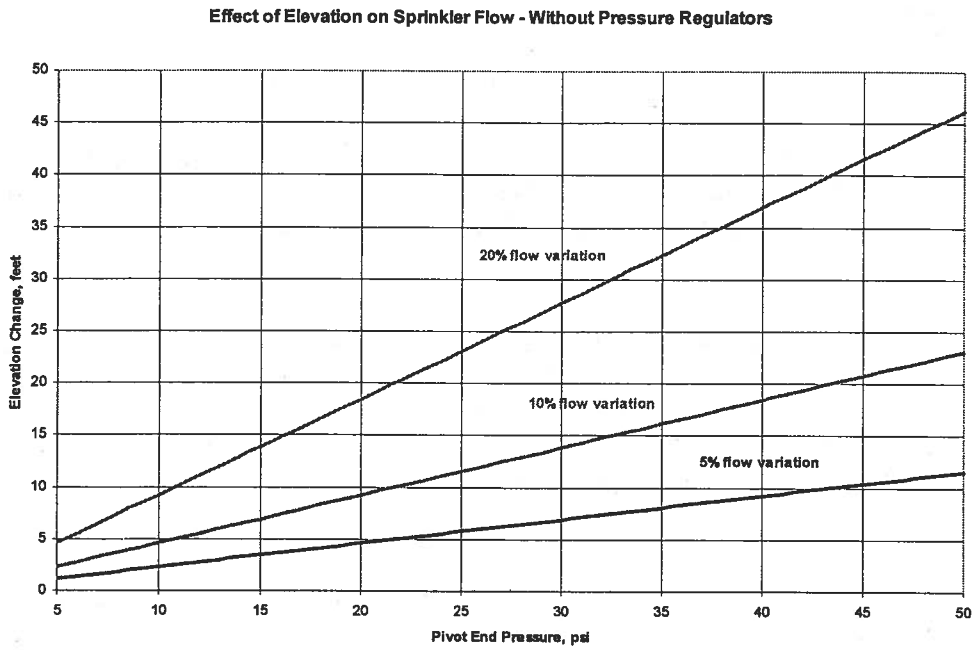
Sprinkler package selection for the center pivot has evolved over the years from wide spaced high angle brass impact sprinklers to a variety of sprinklers. The use of the high angle sprinkler has been replaced by lower operating pressure sprinklers with the majority being sprays, although low angle impacts made of both plastic and brass are still used in some supplemental irrigation areas. Some of the new sprays utilize rotating devices on closer spacing for improved uniformity that can be operated with energy saving pressures as low as 10 psi.

As these changes have taken place, the basic considerations become important. These include the soil conditions, terrain, and crop. When some soil and terrain conditions are grouped together a very careful review of the cropping practices, machine flow, and type of sprinkler selection become very critical for best operating and yield opportunities.

As the sprinkler type has been changing, another significant change has also been taking place. This involves using drops to lower the sprinkler from the top of the pipeline down nearer or into the crop canopy. Research has proven that this change can result in reduced evaporation and other losses related to wind drift. The guideline for this reduced evaporation is 1% gain for each foot of drop from the pipeline, up to a maximum of 10% water saving in some conditions.



The proper design of the sprinkler package now must include many factors to provide proper distribution and prevent excessive runoff. Some of the factors are field slope, soil texture, crop canopy height, sprinkler pressure, and sprinkler type. With the adoption of low-pressure sprinklers the slope in the field can become extremely important, therefore the potential need for pressure regulators has become necessary. Generally a 10% variation in water applied is acceptable, therefore the positive and negative field elevation changes should be reviewed.



The lower pressure sprinklers now being used tends to have droplets that are of a size that is not as subjected to movement by the wind as some of the higher pressure units. Although if pressure regulators are not used and excessive pressure is applied to the low-pressure type sprinklers, small droplet can be formed. Various sprinkler types and pad configurations may modify the droplet, such as; deep groove pads produce larger droplets than shallow groove or smooth pads. Each pad type has characteristics that are suitable for the varying crop and/or soil conditions.

When drops are used, the sprinkler height must be coordinated with the crop canopy height, sprinkler type, sprinkler spacing and the drop type. The use and acceptance of the sprinklers placed on drops has grown rapidly. With that growth, various types of materials have been used. The first drop material used was galvanized steel pipe, followed by PVC, polyethylene, and flexible hose. The application of these materials depends on many factors.

The first item to consider when using drops is the material type and configuration of the device to deliver the water from the top of the machine pipeline and direct it down to the crop. Steel, aluminum and PVC "U" pipes or loops have been made to accomplish this task. These will have an offset ranging from 6 to 20 inches between the legs. The longer lengths allow the drop to be placed exactly between the row if desired, if the crop is planted in a circle. The "U"pipes are also made with configurations ranging from both male and female pipe threads to hose attachment barbs.

Galvanized steel pipe is used because it produces a rigid structure to mount the sprinkler. The use of steel drops and U-pipes continues to be a viable selection when corrosive water is not present. The length of these drops are generally limited to approximately nine (9) ft. above the soil surface, on standard profile machines, as the wind and crop may cause drop breakage if longer length pipes are used.

PVC drops and U-pipes have also been developed, because of lower cost of the material and their ability to handle corrosive water. The material is semi rigid and sunlight resistant that can withstand most environmental issues. The PVC U-pipe in conjunction with PVC provides increased flexibility when crop interference is encountered. Wind and cold temperatures can adversely affect the life of the threaded connections for this material.

Polyethylene drops, used with either steel or PVC U-pipes, has also become a popular choice in many areas, because of its relative material cost and durability. The material handles corrosive water extremely well and provides a semi-rigid structure. Polyethylene drops are generally black in color and the heat of the sun will cause the drops to bow slightly, depending on the temperature. This will cause the sprinkler to be offset slightly and can affect the pattern of the water.

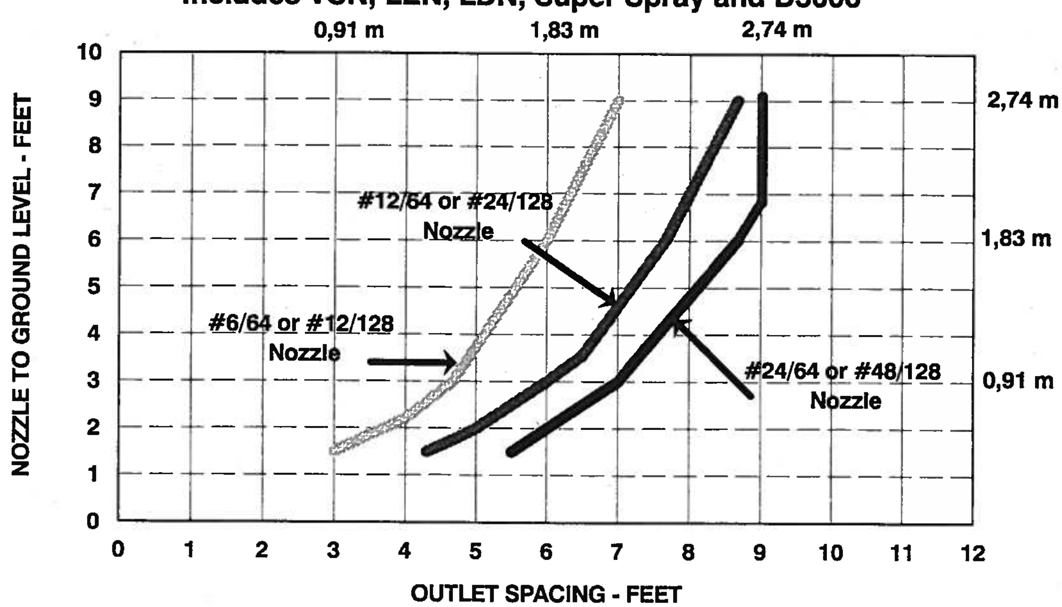
The use of flexible hose drops continues to expand. Flexible hose allows for lowering the sprinkler into the crop canopy for maximum application efficiency. The use of flexible hose also requires a weight to hold the sprinkler down and minimize the sprinkler movement in the wind. The weight must be added near the sprinkler to hold the hose straight and to assist in the prevention of the sprinkler being blown up over the truss rods in windy conditions. A variety of 1½ to 2 lb. weights are being used, ranging from pipe nipples to weights that slip over the hose made from pipe or various plastics. Weights of ¾ and 1 lb. that fit around or on to the sprinkler have been recently introduced which have a smaller surface area for less movement in windy conditions.

With the prevailing winds that are normal in this general area, the droplet size must be considered. The large droplet less movement is seen, although this droplet does not infiltrate into the soil as easy and it can also cause soil compaction of the soil surface. Low pressure can cause large droplets although there are pads and rotating sprinklers that can reduce the number of large droplets and yet produce a gentle application onto the soil and crop.
One of the more important design elements that must be considered is the sprinkler spacing when the unit is lowered near the soil surface. All sprinklers require adequate overlap from the adjacent sprinkler for uniform distribution.

As the discharge of each of the sprinkler types are lowered from the pipeline, the spacing distance between the sprinklers must be reviewed for proper overlap. The crop canopy will also affect the sprinkler overlap. A careful review using various tables and charts which show the proper ratio of spacing to height above the ground, types of pads, and drop material for a properly designed machine with sprinklers and drops to meet your field requirements.

SPRAY NOZZLE SPACING at 6 psi (0,41 bars)

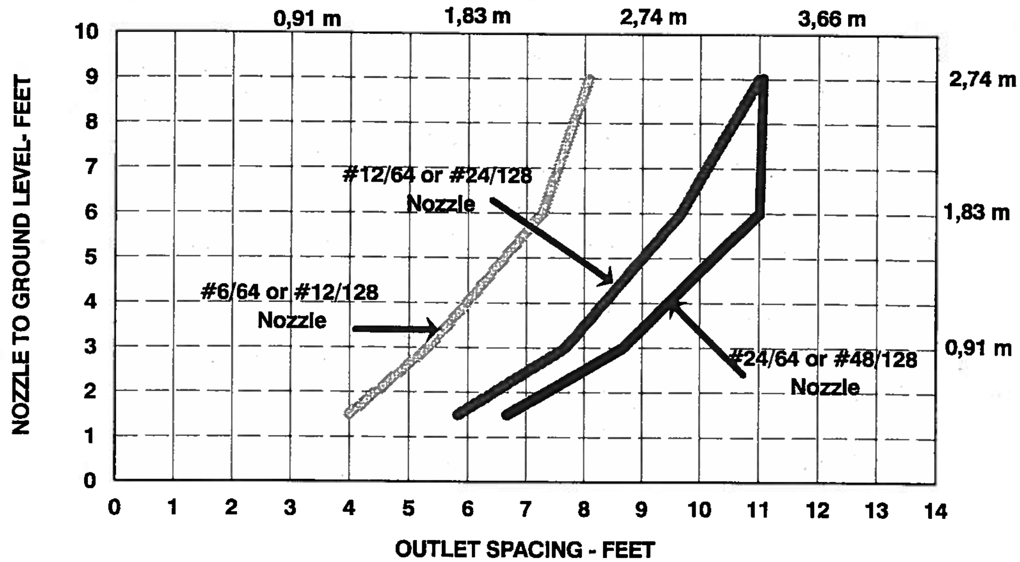
Includes VSN, LEN, LDN, Super Spray and D3000



Flat Grooved Pad, no wind, 150% overlap

SPRAY NOZZLE SPACING at 10 psi (0,69 bars)

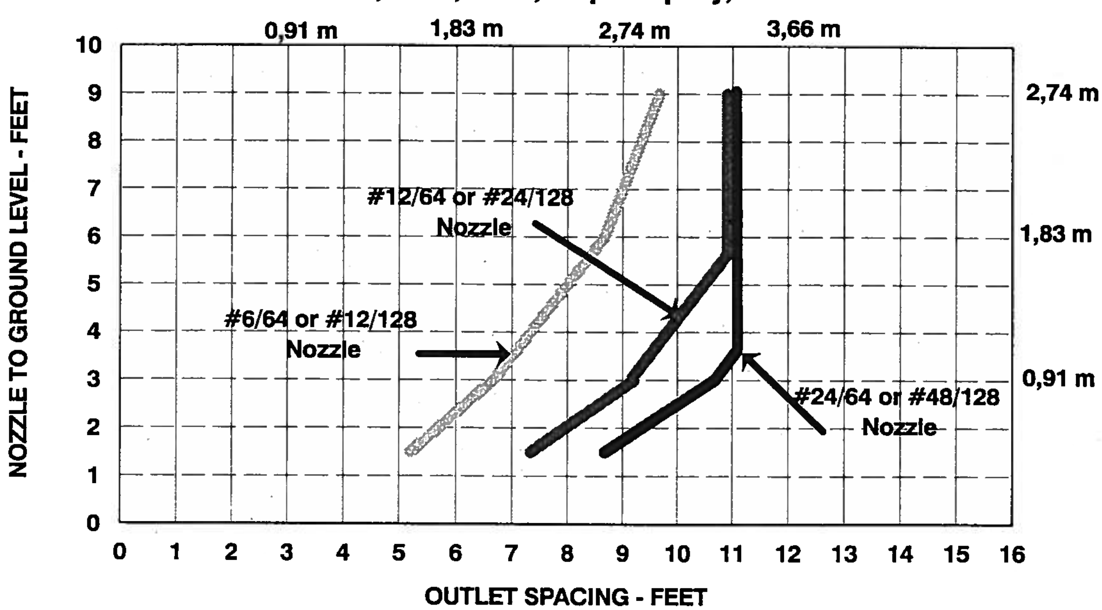
Includes VSN, LEN, LDN, Super Spray, and D3000



Flat Grooved Pad, no wind, 150% overlap

SPRAY NOZZLE SPACING at 15 psi (1,03 bars)

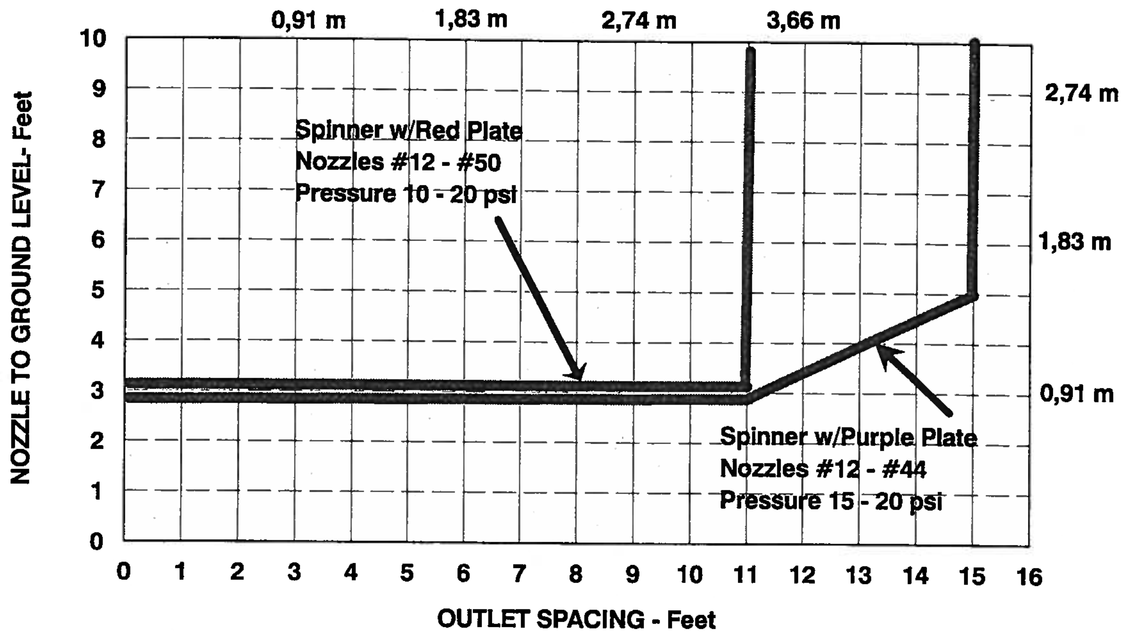
Includes VSN, LEN, LDN, Super Spray, and D3000



Flat Grooved Pad, no wind, 150% overlap

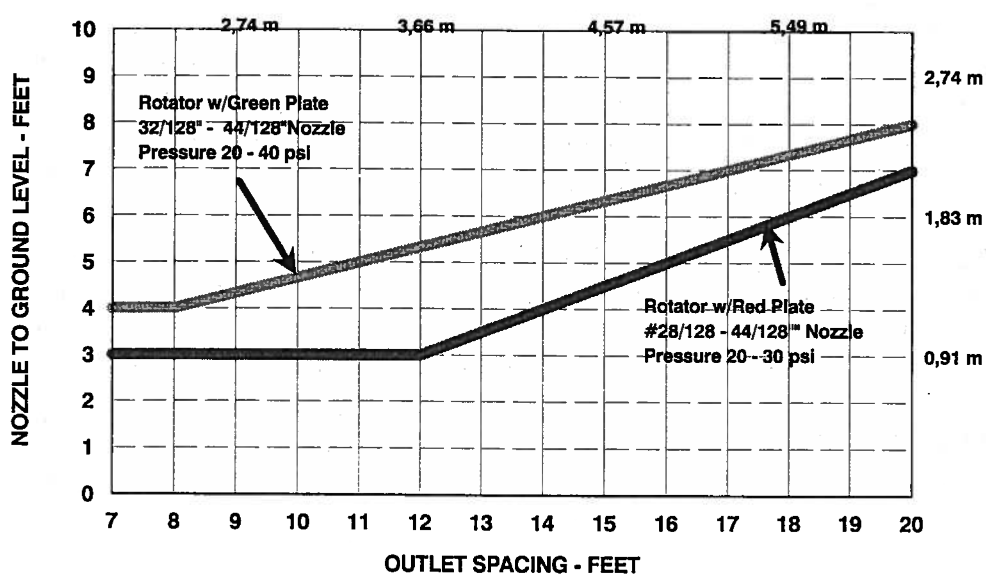
SPINNER SPACING

MAXIMUM



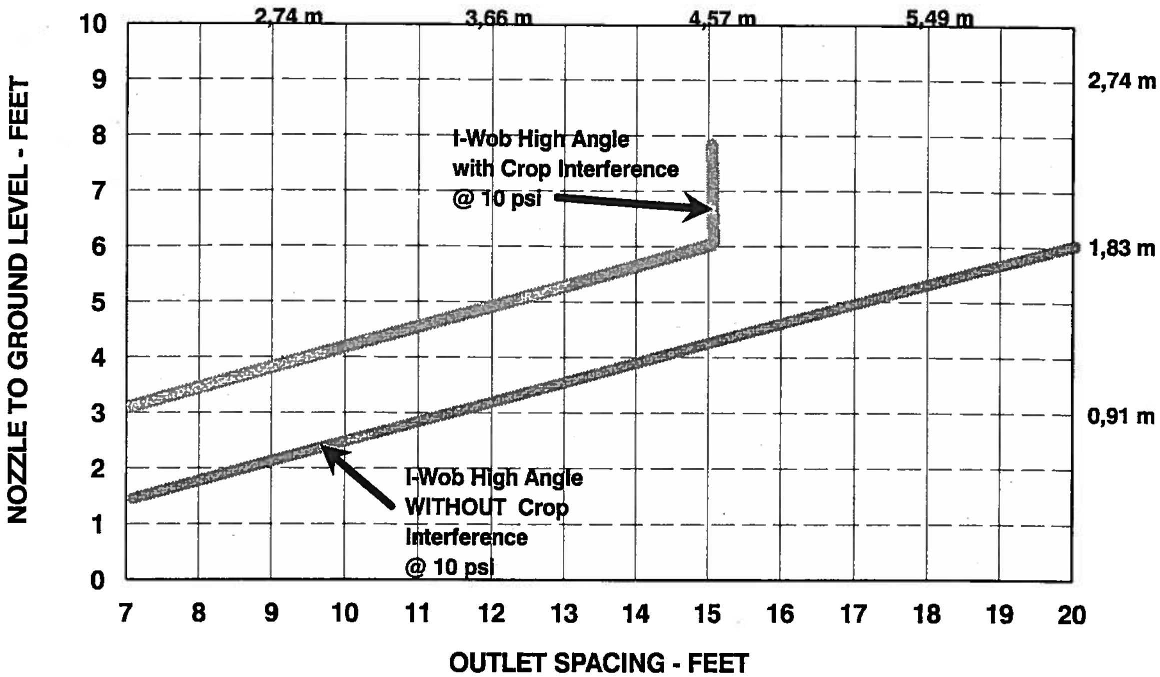
When nozzle is placed on drops 150% overlap

MAXIMUM ROTATOR SPACING



Spacing for maximum width should not exceed approximately 15% of machine length

MAXIMUM I-WOBBLER SPACING



Spacing for maximum width should not exceed approximately 40% of machine length SEE additonal graph
y

The placement of the sprinklers very close to the soil surface has resulted in a concept commonly referred to as LEPA, or Low Energy Precision Application. The concept has resulted in measured application efficiency of up to 98%. The LEPA machines may be equipped with specially designed sprinklers, which are capable of only providing a bubble distribution or normal spray nozzles, which may be covered with a sock or tube for distribution directly into the furrow. On pivots, this usually involves planting the crop in a circle, whereas on linear machine, the furrow, are placed parallel to the wheel tracks.

The design of the sprinkler package may also include special methods and/or devices to keep the wheel track of the machine in a relatively dry area during the operation. This can involve using the drag sock or LEPA units adjacent to the wheels. Another method is to use boombacks or offsets, which are extensions behind the wheels in the direction of travel where 180° sprays are used, thus applying the water behind the wheels.

Upon the installation and/or after the initial or seasonal operation, it is important that you make checks concerning the sprinkler package. Ensuring that your sprinklers are operating at the correct pressure is one of the most important checks that you can make. Several items you will need are: 1) the correct sprinkler chart 2) accurate pressure gauges. Check the pressure at the pivot point and compare it to the value on the sprinkler chart. The pivot pressure must be measured at the top of the pivot elbow and compare it to the chart value. You should also check the pressure at the end of the machine or the last sprinkler. For both of the checks, the machine should be located so that it is at the highest point of elevation in the field and if it has an endgun, it should also be operating.

Checking the pressure is one of the most important items to check. If the sprinkler package is designed to operate at 20 psi at the end of the machine and it is only operating at 15 psi, a 15% reduction of water is being applied. In most locations pumping conditions can change throughout the growing season, therefore these pressure checks should be performed at least on a monthly basis.

In conclusion the initial design of the sprinkler package is extremely important, yet the operation and maintenance of the machine and sprinklers is also important, which can affect your crop yield and quality results.

MOBILE IRRIGATION LAB (MIL): Center Pivot Uniformity Evaluation Procedure and Field Results

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Introduction

The Mobile Irrigation Lab (MIL) project is an educational and technical assistance program that is focused on enhancing the irrigation water management practices of Kansas irrigators. It is an outgrowth of experiences gained from long-term on-farm demonstration projects in south-central and western Kansas. The MIL field unit is a 16 foot trailer partitioned into a classroom/office area in the front and an equipment compartment in the rear. The front office area allows on-site training and data analysis opportunities. For larger training sessions, MIL computers are used in conference rooms to conduct hands-on computer software training. MIL tools include KanSched, an ET based irrigation scheduling program and FuelCost. A pumping plant efficiency estimator. The bulk of the field equipment carried by MIL are IrriGages. IrriGages are non-evaporating, in-field measuring devices used to catch irrigation applications by center pivot and linear irrigation systems. The catch data can be used to calculate a distribution uniformity coefficient which is a measure of the sprinkler package performance.

MIL Educational Activities

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MIL educational activities have included the traditional classroom/lecture format where program information and study results are presented. Other presentations have been incorporated into agronomic and/or irrigation management meetings and field tours. The special educational focus of MIL has been hands-on computer training for producers and agency personnel. While the bulk of the training has been conducted in a class room setting, using MIL laptops to set up as a computer lab. A unique feature of MIL is the ability to do one-on-one computer training at the field site. The front half of the MIL trailer can easily accommodate 2 or 3 individuals. The laptop computers can also be carried into the home or office of an interested producer.

The ET based irrigation scheduling program, KanSched, has been the primary focus of the computer training sessions, although other software programs are reviewed. Several hundred MIL resource CD's, containing both information and software, have been distributed upon request. MIL resources are also easily accessed via the MIL website at http://www.oznet.ksu.edu/mil/.

Field Activities : Center Pivot Uniformity Testing

MIL has an emphasis on field evaluation center pivot sprinkler packages for distribution uniformity. The initial rational for testing was that if irrigation scheduling procedures result in "just in time, just enough water application", then the water must be distributed so that plants have equal access to the water to prevent over- or under-water within the field, which would have yield implications.

Center pivot systems are the dominate irrigation system in Kansas, representing about 80 percent of the irrigated acres. The sprinkler package design is based on a number of factors with system pressure and flow rate as major considerations. Center pivot irrigation systems have been largely assumed to be properly operating if the pivot point pressure and flow rate are set at the design operating specifications. Routine evaluation of the center pivot sprinkler package after installation is seldom performed by the installer. Testing involves placement of multiple catch containers along the lateral of the system and then measurement of each catch. The catch containers used had to be measured quickly in order to avoid measurement error that would be introduced by evaporation losses. Therefore, a number of individuals had to be present at the test site for quick measurement. Measurement required entry into a very wet field, making for difficult data collection.

Development of a more streamlined testing procedure has been made possible through the use of IrriGages. IrriGages are a non-evaporating collection device as shown in Figure 1. A series of IrriGages are placed along the center pivot or linear lateral and are normally spaced at about 80 percent of the nozzle spacing. The IrriGages are placed so that all water from a complete pass of the center pivot is collected. The data collected includes the volume of catch and the position radius of the IrriGage relative to the center pivot point or the end of the linear system. System operating and package characteristics are also recorded. The catch data is entered into a MIL uniformity evaluation program where the average depth of application and the coefficient of uniformity (CU) value is calculated. The program also plots the catch data which helps to visually identify the location of package weakness.

The MIL uniformity testing program has several goals including 1) development of the testing procedure, 2) development of a data base of characteristic uniformity performance criteria for various nozzle package types and configuration that could improve design and installation recommendations, and 3) improved performance for an individual operator's system.

The MIL evaluation program is limited to sprinkler packages that are at least four feet above ground as three feet of clearance is recommended between the top of the collector and nozzle outlet. Another restriction is the need for the top of the collector to be above the crop canopy or be placed in a non-vegetated strip of a width of about three times the height differential between the collector top and the nozzle on each side of the catch container. The height restriction means many in canopy systems can not be evaluated with the MIL test procedure. However since the in-canopy system is generally affected by the canopy, the uniformity of distribution pattern is not as important as for above canopy systems. A different evaluation procedure is being developed that will involve pressure or flow testing of nozzles at specified positions along the center pivot lateral. All systems, regardless of the type or configuration of the nozzle package, should be inspected regularly and repairs made to meet original design criteria as specified in the sprinkler design package papers that should have been provided at installation.

Test Result Examples

Field test results have found a number of center pivot nozzle packages that were not performing to expectations. Some of the non-uniformity may be related to the original design where possibly the incorrect well yield and pivot pressure was provided to the designer. Some non-uniformity may be due to incorrect input pressure and flow settings sue to well or pump changes or faulty gauge or meter readings. A number of systems were found to have had the package incorrectly installed, while some had performance problems related to nozzle maintenance issues.

The uniformity test results for four systems are shown in Figures 2 through 5. Figure 2 is a rotator equipped center pivot system with a CU of 84 percent. The major spike in application depth in the inner part of this system, was a leaky tower boot. The inner span of many systems have higher than average application depth, as is noted for this system as well.

Figure 3 shows a flat spray system with a very low CU valve of 50 percent. The water supply for this system has very high iron and other mineral content and there was visible accumulation of materials on the system, nozzles and splash plates. Noted in the visual inspection of the system while operating, were a number of nozzles that had a deficient spray pattern, due to either partial plugging of the orifice or crust accumulation on the splash plate.

Figure 4 shows the results from a flat spray equipped system in rolling sandhills near Garden City, Kansas. The non-pressure regulated flat spray nozzles were tested in high wind conditions. During the set up of the test, it was expected that the CU value would be very low due to the elevation differences along the center pivot lateral and the high wind conditions. However, the CU value of 82 percent was much higher than expected. Two leaks are noted as spikes in the application depth. The center point spike was due to continuous over-spray near the center pivot point, due to the high wind conditions. The spike at the mid-point of the system may have been an unobserved leak.

The results for a new system equipped with I-Wob nozzles in Figure 5 showed an increasing depth of application with increase of radius. The application depth was approximately one-third greater in the outer portion as compared to the inner portion. This is the most problematic of the examples shown, but the cause may be related to improper flow or pressure conditions. The CU value of 82 percent was surprising good, however, the variation in average application down the lateral needs to be addressed.

Other tests have revealed installation problems, such as missing drop nozzles and reversal of tower nozzle sequences. Poor performances have also been attributed to changes in operating conditions as compared to original design specifications. Another possible cause of low uniformity could be internal incrustation similar to the material encrusted on nozzles splash types, which would alter friction loss characteristic of the system resulting in loss of design integrity.

Future Activities

Development of additional decision-support software and computer training activities will continue. Distribution of the information will continue via educational meetings, conferences and training sessions. However, the latest resource materials are available via the web at www.oznet.ksu.edu/mil. Refinement of the uniformity evaluation procedure will continue but an immediate goal will be to develop an IrriGage test kit which would include testing procedure instruction, IrriGages, and data forms and other necessary test equipment. Test kits would be made available for use by producers or agency personnel to increase the number of systems evaluated.

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Figure 1. Series of IrriGages being positioned prior to an evaluation.

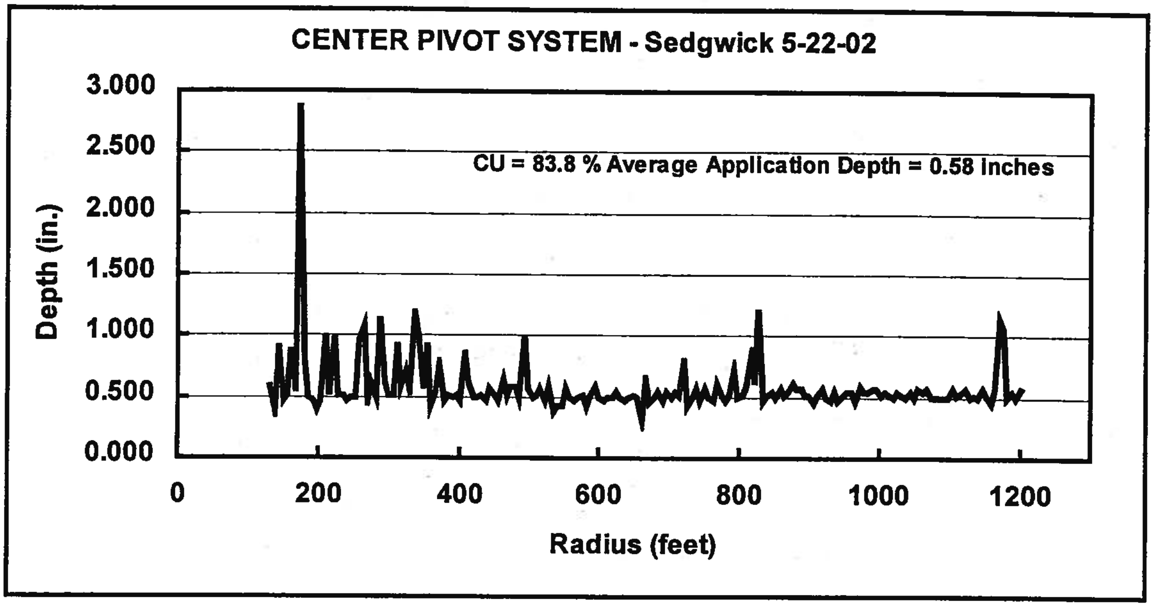

Figure 2. MIL uniformity test results for a center pivot equipped with rotator nozzles.

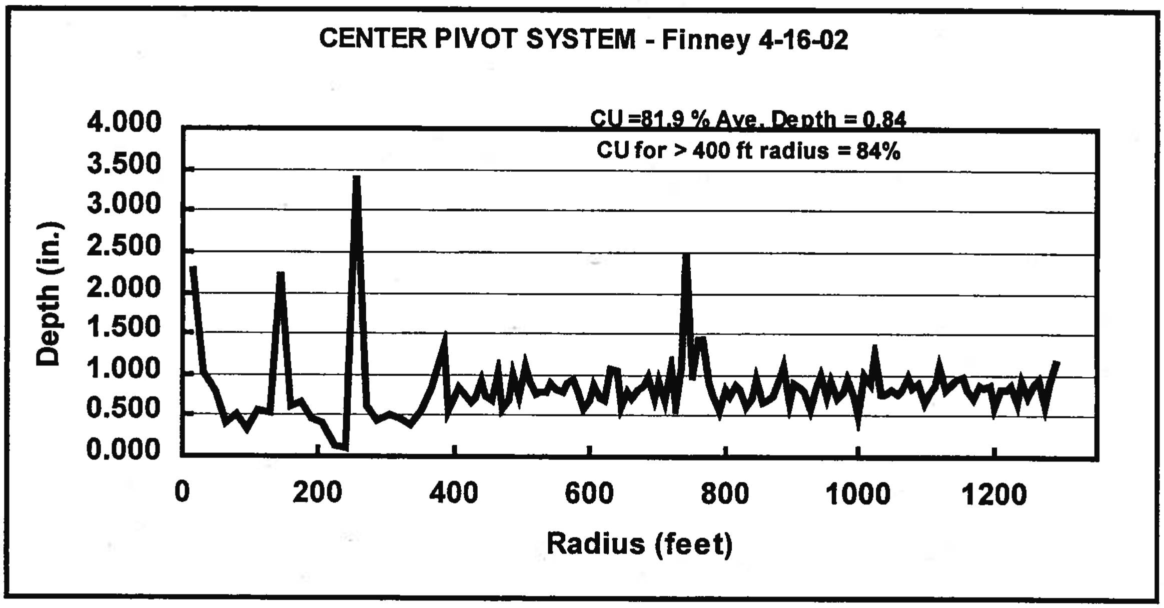

Figure 3. MIL uniformity test results for center pivot equipped with flat spray nozzles.

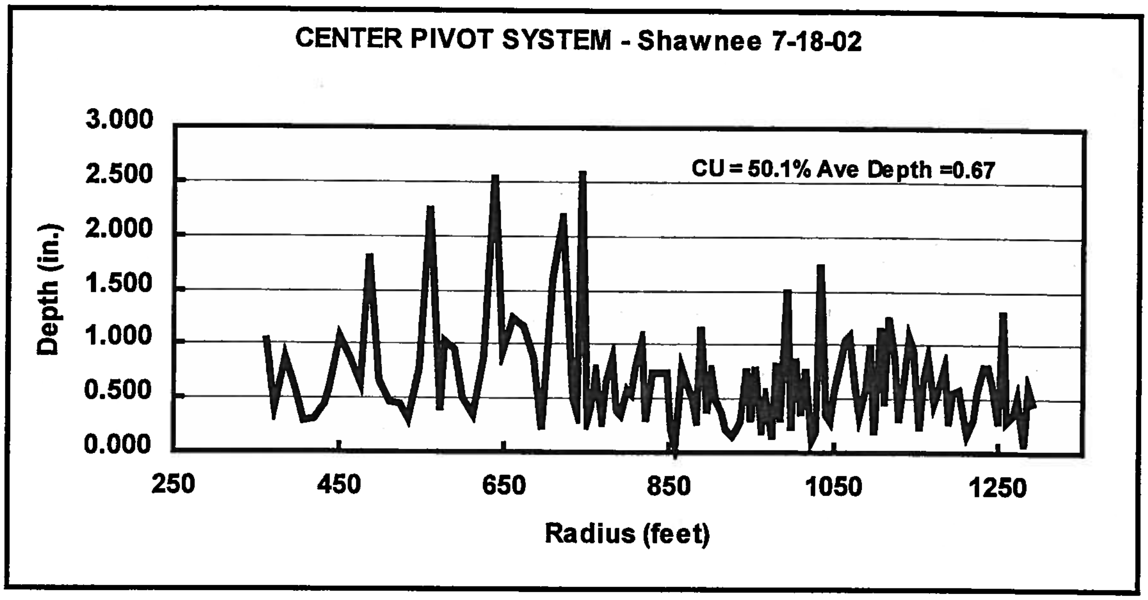

Figure 4. MIL uniformity test results for a center pivot equipped with flat spray nozzles.

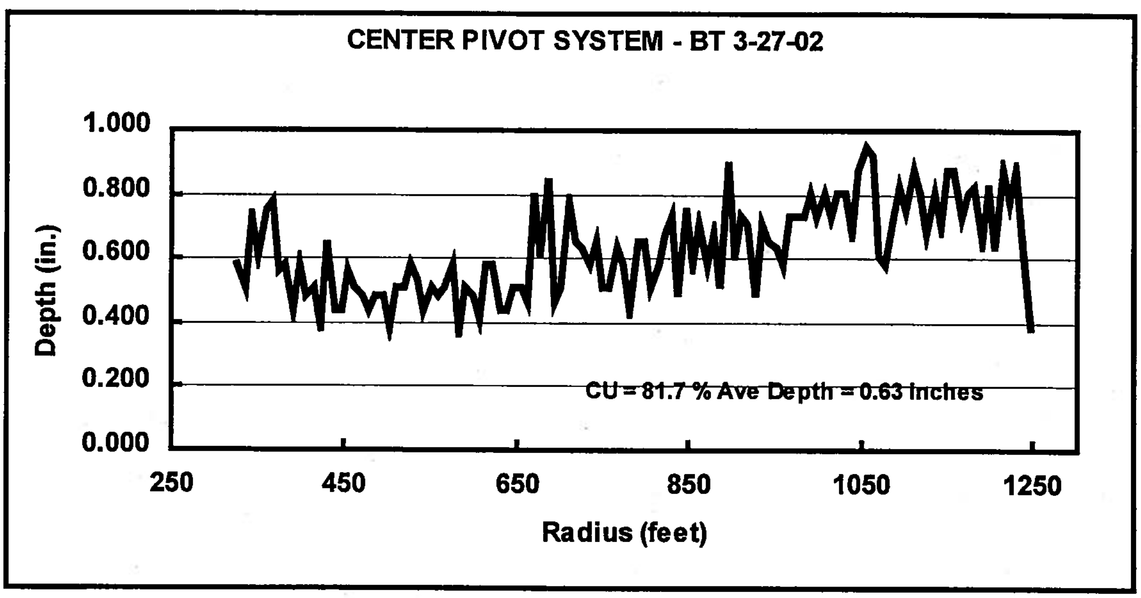

Figure 5. MIL uniformity test results for a center pivot equipped with I-Wob nozzles.

CENTER PIVOT DESIGN AND EVALUATION

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INTRODUCTION

Center pivot irrigation systems have proven to be a water and labor efficient method of irrigation. Acceptance of these irrigation systems began in the early 1960's, and today they are used to irrigate almost one-third of the total irrigated area in the United States. A similar adoption has occurred in many other parts of the world. Center pivot systems require a different procedure to evaluate the uniformity of irrigation for comparison with other irrigation systems. The first recognized procedure for determining sprinkler uniformity was the Christiansen coefficient of uniformity (CU). The definition of Christiansen CU assumes that each catch can, or application depth, represents an equal area of the total irrigated area. To adapt the Christiansen equation for center pivots, area weighting was necessary; since each catch can along the radial line represents a larger area. The objective of this paper is to provide the reader with a familiarity of the Center Pivot Design and Evaluation (CPED) program that is being used by the NRCS for evaluations of center pivot irrigation systems.

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 provides 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. Selecting the appropriate depth for scheduling (Duke et.al. 1992) requires knowing or determining the uniformity of water application to minimize over and under application.

It is often desirable to evaluate systems that have been in service for a number of years to determine changes in performance from the time of installation. Simulations that don't compare closely with design suggest exploring several factors. The major factors that can change a systems performance are a change in nozzle size due to wear, changes in pumping plant efficiency, water supply changes (particularly with ground water decline), system leaks and changes in roughness of the supply and lateral pipe lines. Evaluations should be performed when new systems are installed or existing systems are modified with new sprinkler packages, to assure they operate as designed.

CURRENT EVALUATION PROCEDURES

The most common procedure for evaluating the uniformity of center pivot irrigation systems is to measure the application depth with catch cans. ASAE S346.1, (1999) and National Engineering Handbook, (1983) are the commonly used standards in the US and internationally for evaluating center pivot irrigation systems. The ASAE standard recommends two radial lines of catch cans with the outer end of the rows not more than 50 m apart. The NRSC recommends a single line of catch cans. Both standards recommend calculating the uniformity with the Heermann and Hein (1968) modified equation for the Christiansen (1942) uniformity coefficient. The NRCS includes other measures and performance parameters in their procedure.

The ASAE recommendation to run at night is often not practical for most evaluations. The requirement for low wind is also difficult to satisfy when attempting to evaluate a number of systems. A wind tunnel study (Livingston et. al. 1985) showed that the divergence from 2.5 to 6.2 m/s wind speeds resulted in decreased catches of 5 - 25%. Losses of this magnitude can easily lead to the conclusion that a center pivot system is very inefficient. Evaporation from the catch cans before they are measured also introduces an error in the technique. The standards were developed when impact sprinklers were typically used on moving systems. The current ASAE standard is modified for systems equipped with spray nozzles having significantly smaller pattern radii. The newer spray sprinkler heads often are installed on drop tubes having a wetted diameter of six m or less. The 3 to 4.6 m catch can spacing is not adequate for this small wetting pattern. A typical 380 m system would require more than 400 catch cans for the double row test to satisfy the ASAE standard. This results in evaluation of systems with the newer type sprinkler heads being extremely time consuming and resource intensive. A procedure or process that would provide the needed evaluation information with minimal sampling and use of human resources is an attractive alternative.

EVALUATION REQUIREMENTS

The current standards provide a single estimate of the CU at the time of the test. They require documenting the test and climatic conditions that should be considered when comparing tests between systems. The test however does not provide an insight to the performance of the system as it moves around the circle that is irrigated. The effect of topography and water supply characteristics should also be evaluated. It is a reasonable requirement to suggest that the tests be run under low wind speeds and low evaporation conditions. The NRCS spacing of 9.2 m maximum and ASAE standard 3m could result in errors with smaller radius sprinkler patterns.

ALTERNATIVE EVALUATION PROCEDURE

Computer simulation of the center pivot sprinkler performance was first presented by Heermann and Hein (1968). A user friendly simulation program Center Pivot Evaluation and Design (CPED) is currently being used by the NRCS evaluating center pivot systems. The required inputs and options for the model were presented by Heermann (1990). Edling (1979), James (1984), and Bremond and Molle (1995) have written simulation programs for evaluating different characteristics of center pivot systems. The distinct advantage of simulation over field tests is the large number of design options and operating conditions that can be compared with limited time and resources.

Suggested Protocol for Alternative Procedure

Manufacturers and distributors of center pivot and/or sprinkler heads use computer models to design the vast majority of new or renozzled center pivot systems. Most system designs will provide a uniform irrigation if nozzles and sprinklers are installed according to the design and operated within their intended flow and pressure. The inventory of the manufacturer's computer design provides the majority of the inputs needed to run a simulation of the system to obtain the potential uniformity of the system.

The next step would be to go to the field and perform a physical and visual inventory of the system. The size and length of all pipes, sprinkler model, nozzle sizes, pressure regulators, and location of each outlet should be compared with the design chart and inventory. The elevation of the pivot and each tower is needed for input to the simulation model to accurately solve for the pressure distribution on the system. It is desirable to use pump and drawdown curves but it can be run with constant pressure or discharge. An approximation of the pipe roughness is needed before running the simulation. With the system operating, pressure and discharge measurements should be taken along the lateral line and compared with the calculated pressures and discharges.

Model output includes the hydraulic operating pressures on the system, the sprinkler discharge, the application depth at requested positions and the coefficients of uniformity (Christiansen and low quarter). Differences between measured and computed pressures and discharges suggest that the system may not be performing as desired.

Potential causes of simulation errors are wear, age, or measurement errors of the components, which may cause the initial input to be in error. Factors that can change with age include the pipe roughness factor, pump curve, and nozzle size. Pressure regulators may have a hysteresis effect and could lead to differences between simulated and measured. Age also can change the performance of flow control devices. Measurement is always a potential source of error. This could include measured pressures, discharges, distances and elevation, recognizing accuracy is ± 5% with most standard measuring devices for flow and pressure.

SIMULATION EVALUATION OF CENTER PIVOT SYSTEMS

The simulation model in this paper 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 the 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 applicators.

EXAMPLE 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. Note that the change reduced the CU by 3 percent.

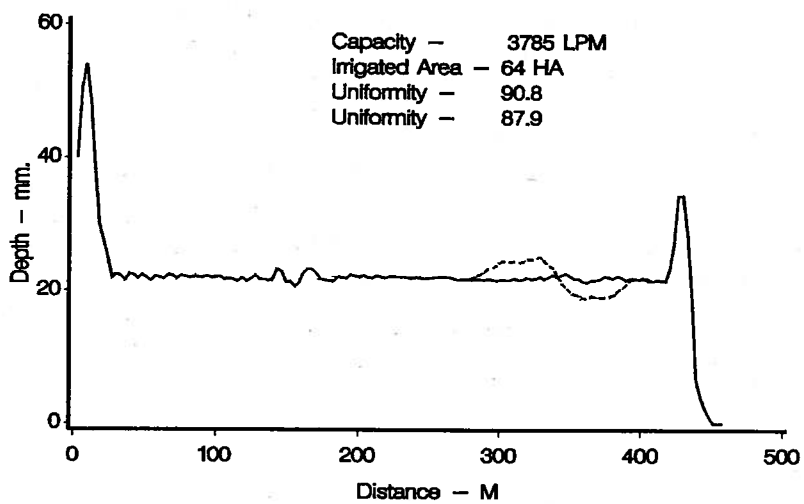

Figure 1 Typical center pivot as designed (CU = 90.8) and with 10 sprinkler heads incorrectly installed shown as a dashed line (CU = 87.9)

THE CENTER PIVOT SYSTEM FILE

The following sections will give more provide an overview of the type of information needed in CPED. It will provide information of the representation of the data and how it is used in the simulation model. The inventory of the system is needed for the simulation. We refer to this information as the Center Pivot System File - or for convenience - The System file. To create a System File have the following information on hand from the manufacturer's inventory:

1. The pump curve or alternatively a constant discharge or constant head with and estimate of discharge. (The pump will be discussed in greater detail later.)

2. The Total Dynamic Lift (ft.), if using a pump curve.

3. The length (ft.) , inside diameters (in.), and the Darcy-Weisbach resistance coefficients for the pump to pivot pipe and the riser pipe.

4. The pipe diameters, starting distances and Darcy - Weisbach Coefficients for the sprinkler pipe.

5. The pivot pad elevation and the height above the soil surface where the pressure is specified(ft.) (Either the pivot height or the sprinkler height if drops are used .)

6. The number of towers, the tower locations (ft.), and the tower elevations (ft.) relative to the pivot pad elevation.

7. The booster pump increase (psi) and the number of sprinklers affected by the increased pressure (used with end guns).

8. The sprinkler brand and model # of each sprinkler on the system. (This will be discussed in much more detail later.)

9. Distance (ft.), range nozzle diameter (64th in.), spreader nozzle diameter (64th in.) for each sprinkler on the system (enter range nozzle for one nozzle sprinklers).

10. The type of pressure control and whether or not there are part circle sprinklers

11. For each pressure controlled sprinkler: the maximum pressure (psi); or the fixed orifice diameter (64th in.).

12. The start and stop angles for each part circle sprinkler.

13. The right and/or left offset for each offset sprinkler.

Some of these items need further explanation:

THE PUMP

Pump Curve

The Head vs Discharge graph for the pump on the system can be used to develop the regression equation that describes the pump.. The program has an option which will fit the pump curve, after it has been given points from the graph. At least 4 points that span the operating range are needed, however 8-10 will give a better fit. 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 also needs to be entered, as most pump curves from the manufacturer are for a single stage. However, if the pump curve comes from field measurements, set the number of stages equal to one.

Constant Head

Rather than using a pump curve, it is also possible to specify a system with constant head or constant discharge. To use a *Constant Head* enter:

Constant Head - psi
Estimate of Discharge at that Head - gpm

Set the number of stages equal to one.

Constant Discharge

To use a *Constant Discharge* enter:
Constant Discharge - gpm

Set the number of stages equal to one.

SPRINKLER BRAND AND MODEL NUMBER

For each sprinkler model on the system, regression coefficients which estimate the coefficient of discharge and the pattern radius, based on the nozzle size and the pressure, are needed. The information provided in the manufacturers' catalogs is used to develop the equations.

Discharge Coefficient

$C_d = Q/(A(2gH)^{1/2})$
where:

C_d - discharge coefficient
Q - discharge, from catalog - cfs
A - equivalent area of the nozzle orifice - ft^2 ; $A = PI*(D_R^2 + D_S^2)/4$
D_R - range nozzle diameter - ft
Ds - spreader nozzle diameter - ft
g - gravitational constant - 32.2 ft/sec/sec
H - sprinkler pressure, from catalog - ft

These units are chosen for calculation such that C_d is dimensionless and between .9 to 1 for most manufacturers. Enter the catalog information in a spreadsheet, and use it to convert to the appropriate units and calculate the discharge coefficients. Once the discharge coefficients are calculated for the various combinations of pressure and nozzle radius, the regression equation to predict C_d can be fit. If the spreadsheet won't do multiple regression, export a file containing C_d, D^2, and H, and use a statistics package that will. The equation is:

$$C_d = B_0 + B_1 D^2 + B_2 H$$

where:

C_d - discharge coefficient
D^2 - equivalent nozzle radius - ft^2; $D^2 = (D_R^2 + D_S^2)/4$
H - sprinkler pressure - ft
B_0 - Intercept
B_1 - Slope on D^2
B_2 - Slope on H

Pattern Radius

An equation that can be used to predict pattern radius based on range nozzle diameter and pressure is developed in an analogous manner. That equation is:

$$R = B_0 + B_1(D_R^2 H) + B_2(D_R^2 H)^2$$

where:

R - Pattern radius - ft
D_R - Range nozzle diameter - ft
H - Pressure - ft
B_0 - Intercept
B_1 - Slope on $D_R^2 H$
B_2 - Slope on $(D_R^2 H)^2$

Enter the data consisting of the *Pattern Radius*, the *Range Nozzle diameter*, and the *Head* from the manufacturer's catalog into a spreadsheet. Use the spreadsheet to make the units conversions and calculate D_R^2H and $(D_R^2H)^2$. Then export an ASCII file containing R, D_R^2H, & $(D_R^2H)^2$, to use in a statistics package that will fit multiple regression.

This pair of equations needs to be developed for each sprinkler used in a simulation. They are used in the simulation program to calculate the discharge and the pattern radius of each sprinkler in order to get the depths. Also needed is its minimum operating pressure in psi. We provide a data base containing the sprinklers we have fit.

RELATIVE ELEVATIONS

The relative elevations of the pivot pad and the towers are used to determine the slope changes of the system, therefore actual elevations aren't needed. The pivot pad elevation needs to be arbitrarily set high enough so that none of the tower elevations are negative. The tower elevations then are set so that they are equal to the pivot pad elevation plus or minus the elevation change for each tower. The default value of 100 ft. for the pivot elevation is usually adequate. Both the pivot pad elevation and the tower elevations are at ground level.

PIVOT HEIGHT

The pivot height is the distance that the sprinklers are located above the ground. If the sprinklers are on drop tubes, adjust the height accordingly.

SPRINKLER PATTERN

There are three sprinkler patterns available in the program. They are: triangular, elliptical, and donut. These are associated with the sprinkler model used. In general high pressure single nozzle systems have triangular patterns, dual nozzle systems have elliptical patterns, and low pressure spray systems have a donut pattern. When running the program, specify triangular =1, elliptical = 2, and donut = 3. See Figure 2 .

START-STOP ANGLES

The start and stop angles for a part circle sprinkler are defined by imagining standing at the pivot and looking out along the pipe. 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. See Figure 3.

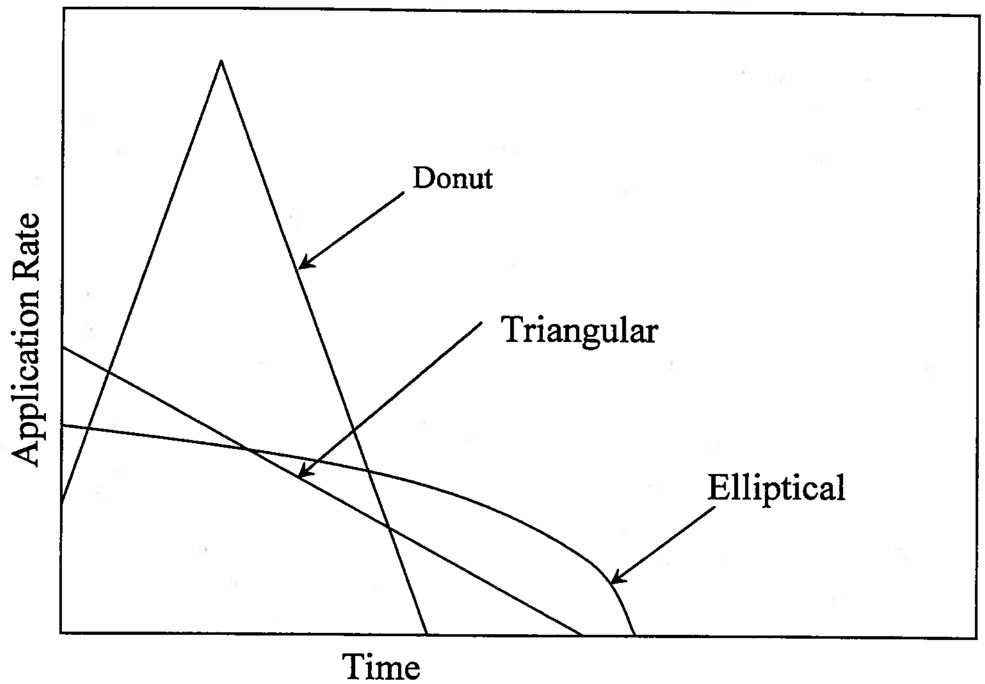

Figure 2. Sprinkler pattern definitions.

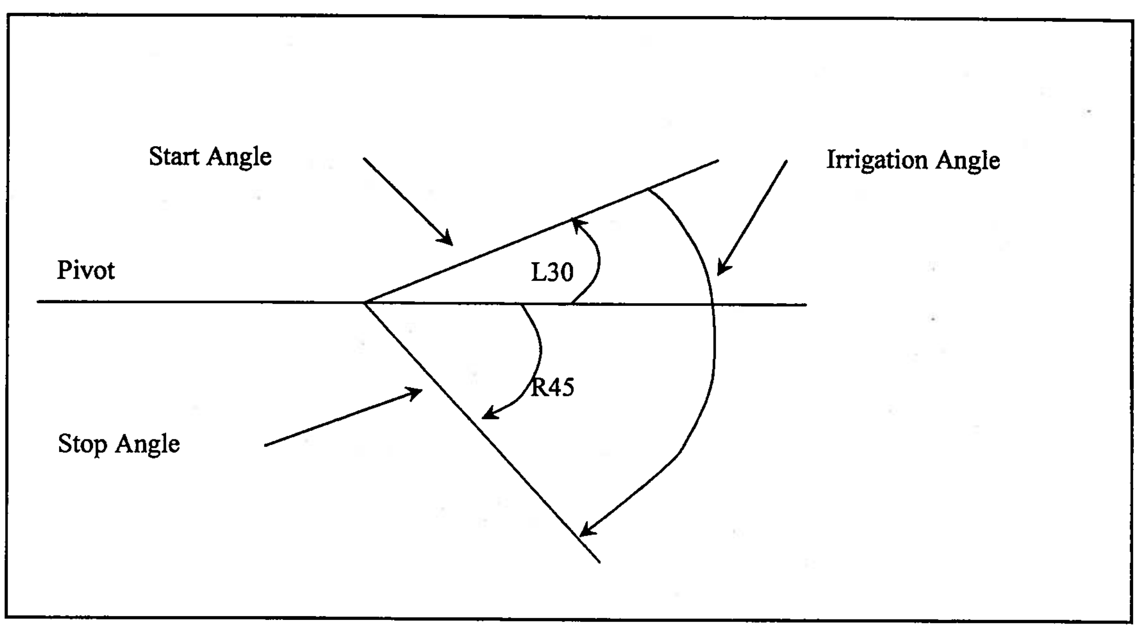

Figure 3. Determining part circle sprinkler angles.

RUNNING THE SIMULATION

Once the System File is complete, the simulation can be run. A few parameters are entered at runtime.

1. Hours/Rev - The time needed to complete one revolution of the Pivot. This directly determines how much water is applied.

2. Sprinkler Number - The program can simulate the water application from either 1 specific sprinkler, or the overlap of all sprinklers on the system. To simulate one sprinkler, enter the number of the sprinkler. To simulate all sprinklers, enter All.

3. Starting Distance for depth simulation (ft.).

4. Stopping Distance for depth simulation (ft.).

5. Distance Increment - The distance between the simulated catch cans (ft.).

6. The Minimum Depth for Uniformity (in.)

Once these parameters are entered, start the simulation.

RESULTS

As the simulation runs, depths vs distance are plotted on the screen. Once the simulation is completed, the simulated depths and the overall system information are provided. Overall system information includes:

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:

1. The line pressure - psi
2. The nozzle pressure - psi
3. The discharge - gpm
4. The pattern radius - ft

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

CATCH CAN DATA

In addition to simulating a Center pivot system and analyzing it's uniformity, Catch Can data can be entered for uniformity analysis, and saved for future comparisons.

DISCUSSION OF EVALUATION PROCEDURES

Evaluations of center pivot simulations were compared against catch can spacing (Heermann and Spofford, 1998). Catch can data had significantly more variation than the simulated values but approximately the same average depths. The sprinklers were spray nozzles with deep grooved pads producing distinct streams and large drop sizes. The catch can test was repeated on the same system by replacing the pads with smooth pads. The catch can CU increased by 10% when changing from the deep grooved pads to the smooth pads. The distinct streams are not measured correctly with small (10-20 cm) catch cans.

The particular objective for evaluating a center pivot system should be considered when selecting the evaluation procedure. If the objective is to consider modifications to improve the uniformity, there is a distinct advantage in using the simulation model procedure. Once the distribution uniformities are calculated with the existing system, it is quite simple to propose changes and simulate the improvements.

Disadvantages of catch cans

- Wind
- Night Testing
- Evaporation
- Difficulty in catching streams from grooved pads
- Small pattern radii – large number of cans
- Extreme care to set cans level and at proper distance
- Labor intensive

Advantages of catch cans

Provides visual real field data of actual conditions
Simple to install
More readily accepted by user or system owner
Does not need a computer

Disadvantages of Simulation

Difficult to obtain pump curves
Difficult to obtain elevation data.
Requires labor to verify field installation
Need drawdown water level
Must have understanding of running models
May need additional measurements if simulation disagrees with field data
Need to know pattern shapes for application devices

Advantages of Simulation

Less labor intensive to obtain field pressure and discharge data
Wind is not a problem
Provides a complete hydraulic analysis for comparison with field data
Measurement errors of catch cans eliminated
Modification or design can easily be evaluated
Used to analyze for potential problems
Aids in identifying pump problems
Allows analysis of changing drawdown
Successive runs with water table changes
Can be used to recommend design changes
Analyze effects of elevation changes for a particular field
Analyze effect of big-gun operation

CONCLUSION

Simulation models can effectively be used in the evaluation of center pivot systems. Advantage of a simulation procedure is the speed of evaluation of an existing system and system modifications. The simulation model can also be used to determine the distribution over the entire field as the topography varies and big gun sprinklers are turned on and off. It also can be an effective tool for diagnosing distribution problems of a center pivot system. Procedures need to be developed to effectively use the simulation for detecting and interpreting the cause of differences between the field measured and simulated system pressure and discharge.

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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 the result of water stress on the crop is not completely 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.

The impact of sprinkler spacing on corn yield was the focus of a University of Nebraska project in which yield data was collected from center pivots at several sites across Nebraska. Kansas State researchers conducted several research experiments to determine the impact of sprinkler height on water distribution. The results from these studies will be discussed.

Field Evaluation of Sprinkler Spacing

To evaluate rings showing up in Nebraska fields, a series of field samples were collected to determine cause and impact. Many center pivot systems are designed with wider sprinkler spacing for interior spans and closer sprinkler spacing for the outer most spans where additional sprinklers are needed to meet application requirements. When possible, yield samples and soil moisture data were collected in this transition area 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. Corn rows were identified within each sprinkler device spacing section of the pivot. In other words, in those areas with wide spacing or those with narrow spacing. Samples were then collected from those rows of corn that were between a series of three sprinkler devices, regardless of sprinkler spacing. Corn yield was determined by sampling 10 feet of row. Soil water content was measured to a depth of 4 feet at one location within each sampled row.

The results of field measurements at the different sites are shown in the following figures. As can be seen, the yield at a number of the sites declined between the sprinkler devices when sprinkler spacing was approximately 19 feet while yield tended to be more uniform for the narrow sprinkler spacing of 9 feet.

Because soil water data was collected at the end of the season when the crop was mature, some of the differences in soil moisture content may have been eliminated with late season precipitation or added irrigation. However, a number of the sites still show soil water levels at the 4 foot level to be much less in the rows that are located directly between two sprinkler devices. Site description and yield and soil moisture results are discussed below:

McCook site 1 had sprinkler devices spaced 6 ft apart and located in the corn canopy at alternating heights of 3.0 and 4.5 ft. Soil moisture was nearly constant across the rows while yield was nearly 25 bu less in the row directly between the sprinklers.

McCook site 2 had sprinkler devices spaced 10 ft apart at an 8 ft height. At this height, the sprinkler devices were out of the canopy for the bulk of the season. Soil moisture content was constant among the rows and yield varied by approximately 15 bu/acre.

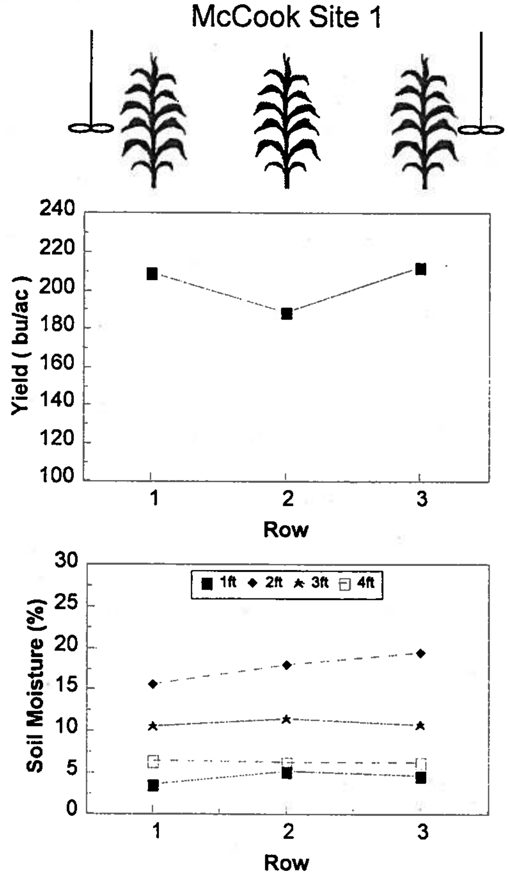
Sprinkler devices were spaced 19 ft apart at a height of 2 ft at McCook site 3. Although yield was similar, soil moisture content declined by nearly 10 % when comparing the row next to the sprinkler device to the row furthest from the sprinkler device.

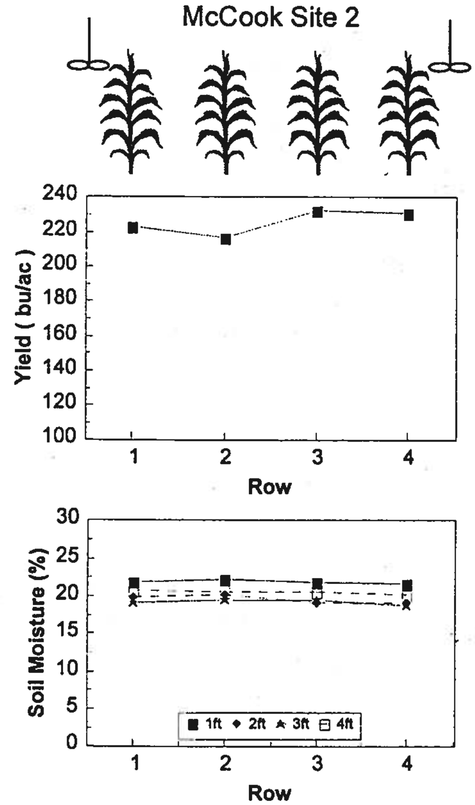
At the Hay Springs sites, data was collected for both wide and narrow sprinkler spacing within the same field. Hay Springs sites1 and 2 were from one field and Hay Springs sites 3 and 4 from another field. Hay Springs site 1 had sprinkler devices located at a 7 ft height and spaced 9 ft apart. There was no reasonable pattern for either yield or soil moisture content at this location. At Hay Springs site 2, sprinkler devices were also at a 7 foot height but spaced 18 feet apart. Soil moisture differences were not detectable at the end of the growing season but corn yield did decline by approximately 25 bu/acre as the distance increased from the sprinkler devices.

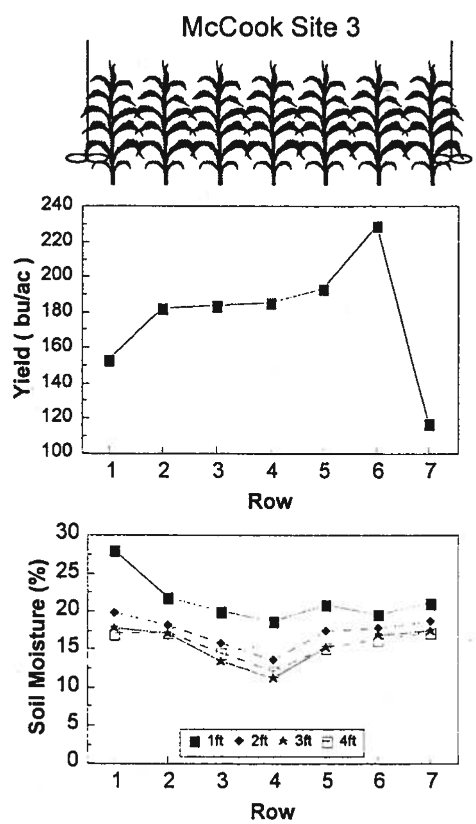
Hay Springs site 3 had sprinkler devices spaced 9 ft apart at a height of 7 ft. No differences can be seen in soil moisture content and corn yield averaged approximately 215 bu. At Hay Springs site 4 sprinkler devices were spaced 18 ft apart at a height of 6.5 ft. Both soil moisture content and corn yield declined for the rows furthest from the sprinkler device. Corn yield dropped from over 220 bu/acre to less than 180 bu/acre.

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.

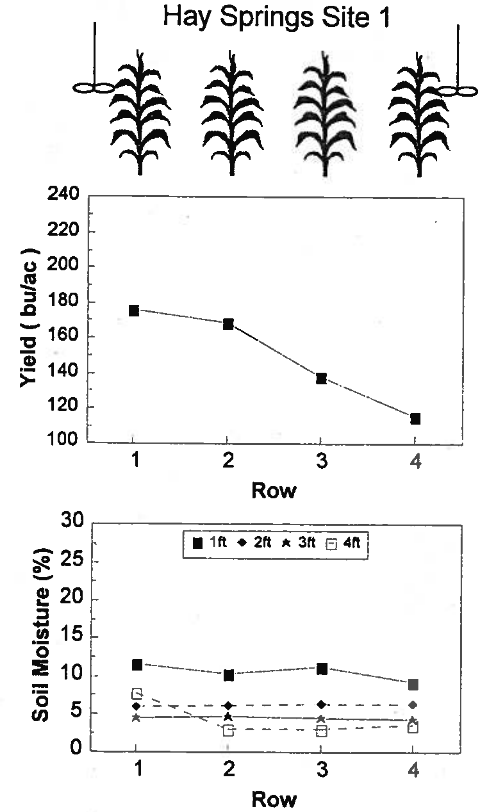
McCook Site 1



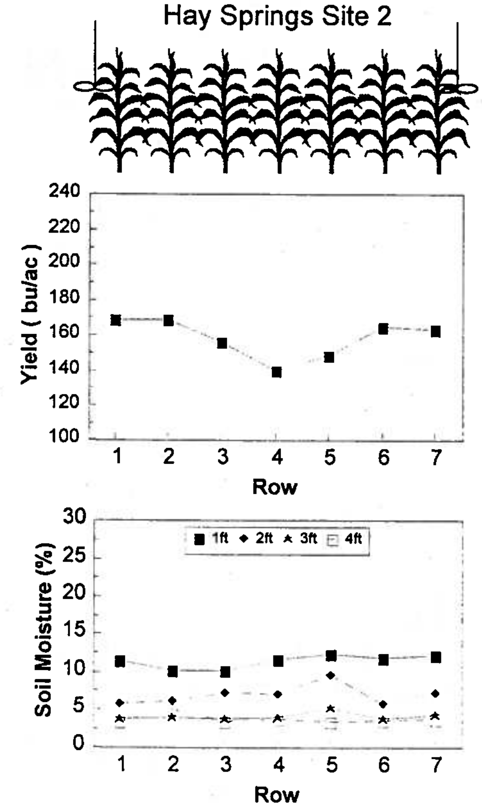

McCook Site 2
Yield (bu/ac)
240
220
200
180
160
140
120
100
1
2
3
4
Row
Soil Moisture (%)
30
25
20
15
10
5
0
1ft 2ft 3ft 4ft
Row


McCook Site 3
Yield (bu/ac)
240
220
200
180
160
140
120
100
1
2
3
4
5
6
7
Row
Soil Moisture (%)
30
25
20
15
10
5
0
1ft 2ft 3ft 4ft
Row

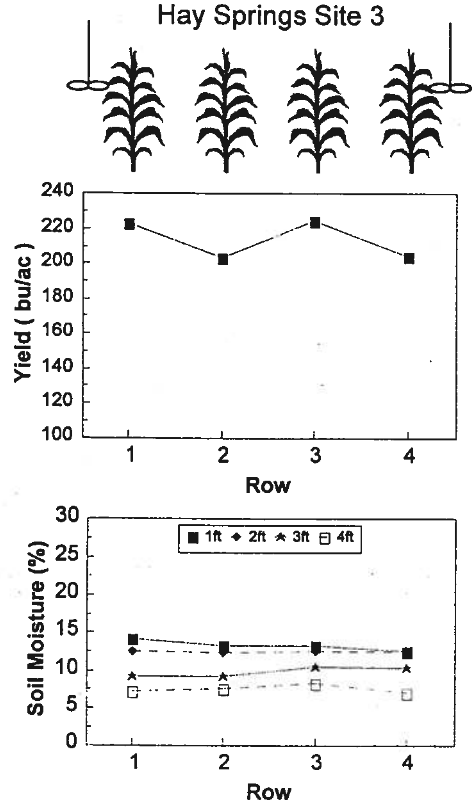
Hay Springs Site 1



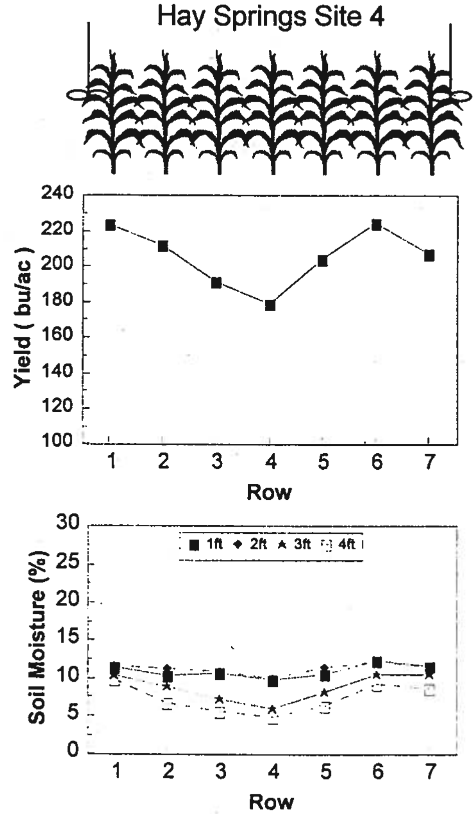
Hay Springs Site 2



Hay Springs Site 3



Hay Springs Site 4



Effect of sprinkler height on corn production

The first project by Kansas State University was conducted from 1983-1986 at Northwest Research-Extension Center on a Keith silt loam soil with land slope of less than 0.5% to compare high pressure (60 psi) impact sprinkler system and a low pressure (20 psi) spray nozzle system. The impact sprinklers were at a height of approximately 13 ft. The spray system was equipped with drops, leaving the nozzles approximately 7 ft. above the soil surface. The spray nozzle was within the corn canopy after tasseling. Corn production was compared under four different tillage systems (Conventional chisel in fall followed by spring disking, Conventional plus corrugation at corn lay-by, Conventional plus furrow basins at corn lay-by, and No tillage) for both impact and spray nozzles. Irrigation amounts were the same for each sprinkler package at 1.5 inches/event and the system capacity simulated a 575 gpm center pivot covering 125 acres.

The results from the study indicate controlling runoff is a key area in optimum management of center pivot systems. In general, higher yields were obtained with the spray nozzle system as long as runoff was controlled by surface modification or residue management (Figure 1). However, in the absence of runoff control, the impact sprinkler was much better. This was particularly evident in 1983, when secondary tillage was critical in attaining high yields under the low pressure spray system. Conventional yields of only 140 bu/acre as compared to 176 bu/acre for the furrow basin treatment were obtained under the spray nozzle system in 1983. Furrow basins have increased yields by an average of 3 to 12 bu./acre for the impact and spray systems, respectively (Figure 1).

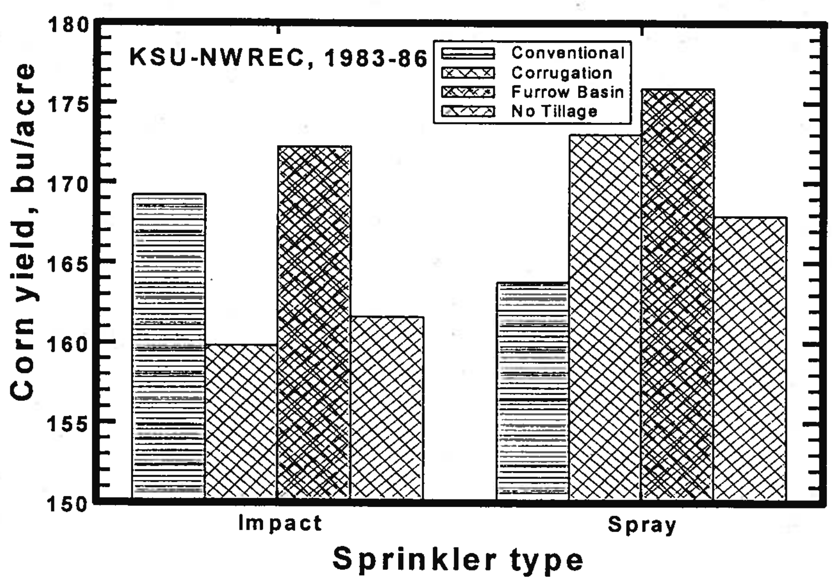


Figure 1. Corn grain yields as affected by sprinkler nozzle type and tillage management, Colby, Kansas, 1983-1986.

It has been a common practice for several years in northwest Kansas 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 in-canopy sprinklers at a height of 16-24 inches that may experience pattern distortion for more than 60 days of the irrigation season. Assuming a 50% distortion for the lower sprinklers beginning 30 days earlier would result in irrigation for some rows being approximately 40% less than the needed amount. Yield reductions would be expected for the latter case because of the extended duration and severity.

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 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 low-energy precision application (LEPA) package to perform better than spray nozzles at limited irrigation capacities and worse than the spray nozzles at the higher irrigation capacities (Figure 2). 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 the water applied in a bubble mode to every other row. The term LEPA often is misused to also 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.

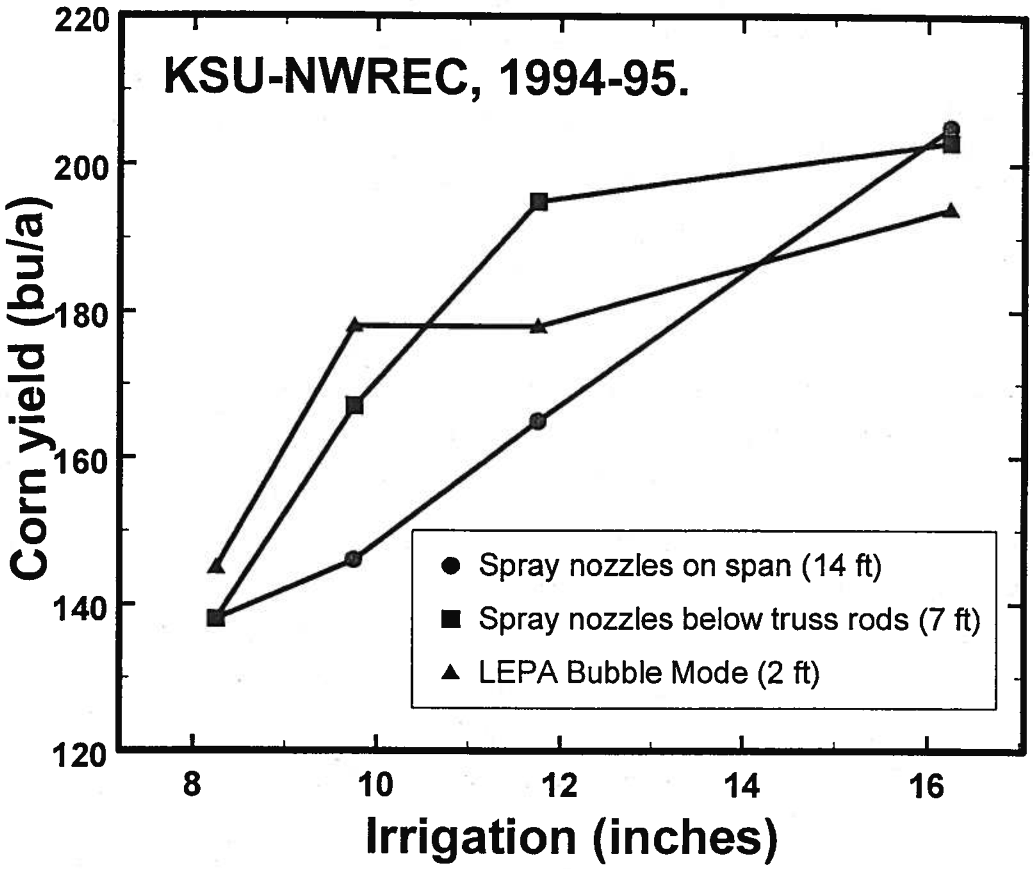


Figure 2. Corn grain yields as affected by sprinkler height and type at four different irrigation levels, KSU Northwest Research-Extension Center, Colby, Kansas, 1994-1995.

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.

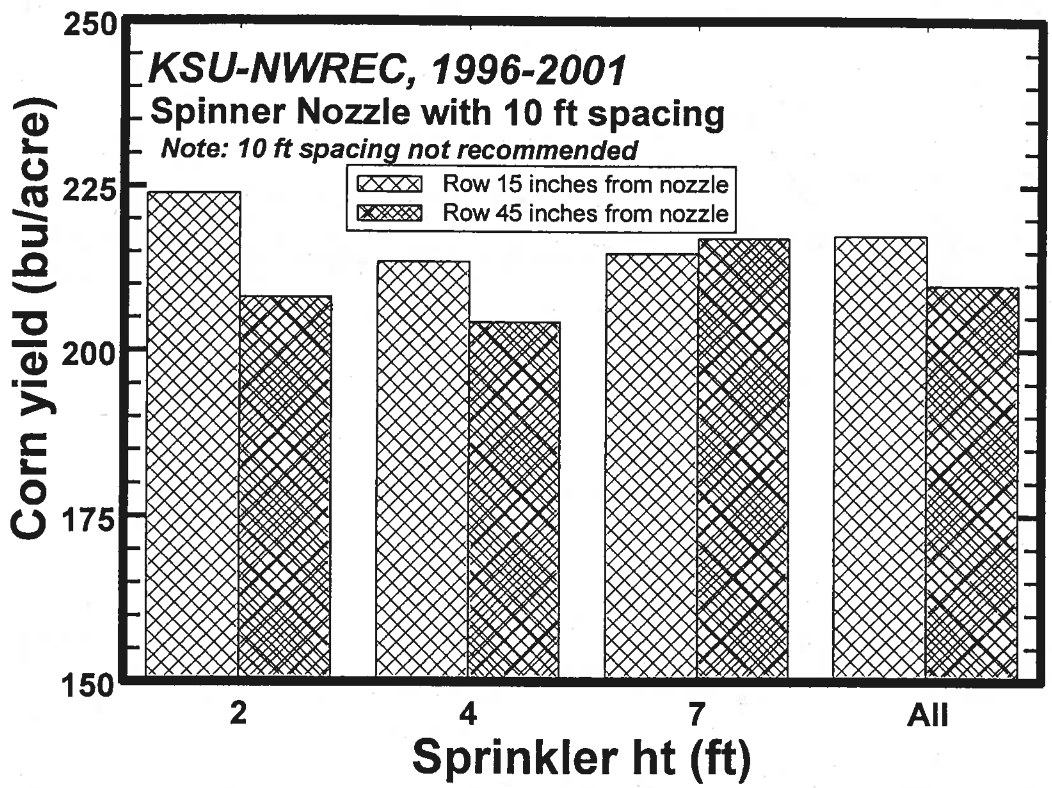


Figure 3. Row-to-row variation in corn yields as affected by sprinkler height in a study with a nozzle spacing too wide (10 ft) for in-canopy irrigation, Colby, Kansas. Data averaged across 4 different irrigation levels. Note: The average yield for a particular height treatment would be obtained by averaging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

MANAGEMENT STRATEGIES FOR A LIMITED WATER SUPPLY

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INTRODUCTION

The Ogallala Aquifer is the major water supply for irrigation in the Central Great Plains. However, in many parts of the Ogallala Aquifer, groundwater levels are declining due to withdrawals greater than the recharge. Many regions face a future without irrigation water supplied by the Ogallala Aquifer. Trends in irrigated and non-irrigated cropland use in Texas from 1964 to 1982 showed that as groundwater supplies became inadequate, irrigated cropland reverted to dryland (Crosswhite et al. 1990). To deter this potential change in agriculture, some regions within the Central Plains have instituted regulations that restrict the amount of pumping. As groundwater declines occur, areas that previously had good producing wells have seen declines in their output. With these changes in well output or regulations, management practices for irrigation must change.

WHAT IS LIMITED IRRIGATION?

When water supplies are restricted in some way, so that full evapotranspiration demands cannot be met, limited irrigation results. Reasons that producer's may be limited on the amount of water that they can apply include:

1) Limited capacity of the irrigation well – In regions with limited saturated depth of the aquifer, well yields can be marginal and not sufficient to meet the needs of the crop.
2) Restricted allocation upon pumping – In some regions that have experienced declining groundwater levels, restrictions have been implemented to decrease the amount of pumping by producers. In some instances, the allocations are less than what is required to fully irrigate the crops grown.
3) Reduced surface water storage – In regions that rely upon surface water to supply irrigation needs, droughts can have a

major impact upon the amount of water accumulations that are available to producers for irrigation.

When producers cannot apply water to meet the ET of the crop, they must realize that with typical management practices, yields and returns from the irrigated crop will be reduced as compared to a fully irrigated crop. To properly manage the water for the greatest return, producers must have an understanding of how crops respond to water, how crop rotations can enhance irrigation management, and how changes in agronomic practices can influence water needs.

There are several important "pieces to the puzzle" that help to facilitate limited irrigation strategies. Many of these principles come from dryland water conservation management. They include: the relationships between grain yield and water use (evapotranspiration), crop residue management for water conservation, plant population management, crop rotations to balance water use, and irrigation timing. These factors will be discussed separately and then combined in actual demonstration/case studies of limited irrigation.

YIELD AND EVAPOTRANSPIRATION

Evapotranspiration is the amount of water that is used by the crop and is the driving force behind crop yields. Water from precipitation or irrigation enters the soil where it can then be used by the crop. Crop yields are a linear relationship to the amount of water that is used by the crop (Figure 1). Crops such as corn, respond with more yield for every inch of water that the crop consumes as compared to winter wheat or soybeans. However, crops such as corn require more water for development or maintenance and can be determined by where the yield-et line intersects the X-axis. Corn requires approximately 10 inches of ET as compared to 4.5 and 7.5 inches of ET for wheat and soybeans. These crops also require less ET for maximum production.

Irrigation is important to increasing ET and grain yields. Irrigation is used to supplement rainfall in periods when ET is greater than precipitation. 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.

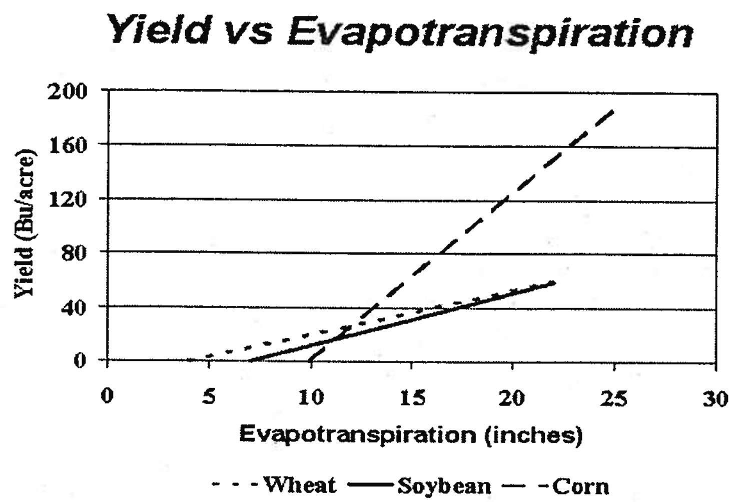

Figure 1. Grain yield vs ET relationship for corn, soybeans and winter wheat from North Platte, NE. (Schneekloth et al. 1991)

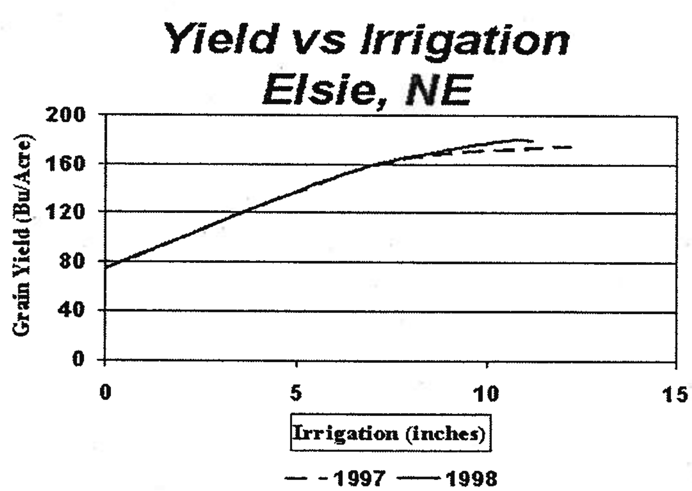

Figure 2. Grain yield vs Irrigation relationship for corn from Elsie, NE.

AGRONOMIC PRACTICES

Residue Management

The goal when working with limited water is to capture every possible source of water in the production system. These sources include rainfall, snowfall and irrigation water. Residue management can have a significant impact upon increasing the availability of water. Producers in the Central Plains have long advocated no-till for dryland production. No-till increases the amount of water stored in the soil due to reduced evaporation from tillage operations and runoff and increased snow catch during winter snowstorms. Changes in tillage management have allowed producers to change rotations from the conventional wheat-fallow rotation to more intensive rotations such as wheat-corn-fallow. The changes in tillage management can be successfully used in irrigated production for moisture conservation.

After harvest, leaving the residue standing can have a major impact upon snow catch. Nielsen (1998) found that standing sunflower residue increased the amount of snow captured in years with strong drifting storms. In most years, standing residue accounted for nearly 2 inches in increased soil moisture over flat residue. In one year, standing residue accounted for nearly 4 more inches of stored soil moisture.

Surface residue during the growing season can also have important impact upon water conservation. Todd et al. (1991) found that wheat residue reduced the amount of evaporation from the soil during the growing season for irrigated corn as compared to bare soil. The reduction in evaporation amounted to nearly 2.5 inches for the growing season. Most of these saving occurred before the corn crop reached full canopy. Water savings from corn residue would be expected to be less since it does not cover the soil completely but some savings would be expected.

Runoff from precipitation is also reduced when surface residue is present. Residue acts as small dams that slow water movement and allow for more time for the water to infiltrate into the soil. Residue also reduces the impact of rainfall and irrigation upon surface sealing which increases infiltration rates. As droplets impact the soil surface, they destroy the surface structure which will seal the soil surface and reduce infiltration rates. Residue protects the soil surface from the impact of these droplets.

Plant Populations

Plant populations for dryland production are less than that for irrigated production. Populations are reduced to reduce ET by the crop to better match precipitation and stored soil moisture. However, when considering to reduce populations on irrigated corn, producers must realize that populations for corn must be reduced to less than 18,000 plants/acre to reduce ET. Lamm and Trooien (2001) found that corn grain yields generally increased as plant populations increased from 22,000 plants/acre to 34,000 plants/acre for varying irrigation capacities. Little yield penalty was observed at higher plant populations compared to lower populations when no irrigation was applied.

Crop Rotations

Crop rotations can have a major impact upon the total water needs by irrigation. Crop rotations that have lower water use crops such as soybean or winter wheat can reduce irrigation needs. Schneekloth et al. (1991) found that when limited to 6 inches of irrigation, corn following wheat yielded 13 bu/acre (8 percent) more than continuous corn. The increased grain yield following wheat was due to increased stored soil moisture during the non-growing season that was available for ET during the growing season.

Crop rotations also spread the irrigation season over a greater time period as compared to a single crop. When planting multiple crops such as corn and winter wheat under irrigation, the irrigation season is extended from May to early October as compared to continuous corn, which is predominantly irrigated from June to early September. Crops such as corn, soybean and wheat have different timings for peak water use (Figure 3).

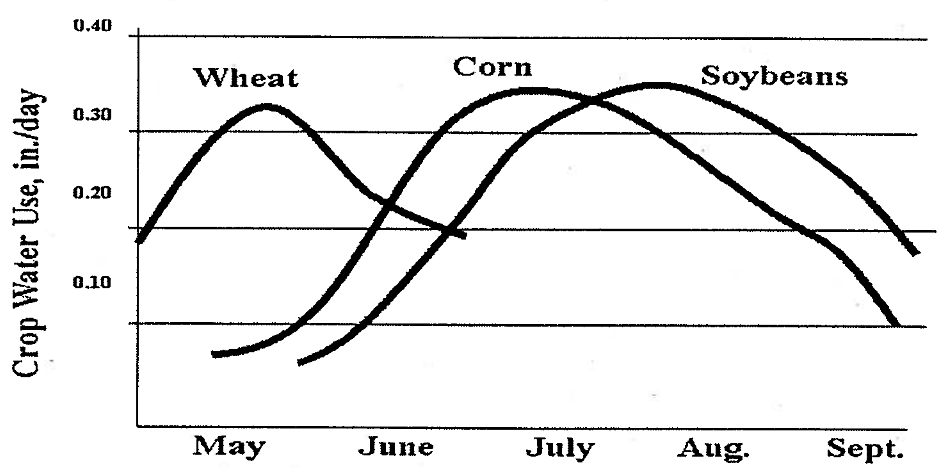

Figure 3. Example of daily ET during the growing season.

With low capacity wells, planting multiple crops with smaller acreages allows for water to be applied at amounts and times when the crop needs the water. The net effect of irrigating fewer acres at any one point in time is that ET demand of that crop can be better met. Irrigation management can be as needed rather than in anticipation of crop ET. With low capacity systems, producers generally irrigate to keep the soil moisture as close to field capacity as possible in anticipation that their system can not meet crop water needs later during peak water needs without precipitation. Some systems can never meet crop ET, even with normal precipitation. O'Brien et al. (2001) found that when irrigation system capacity was increased from 0.1 inches/day to 0.2 inches per day that yields increased 28%. To achieve this change in capacity per irrigated acre, a producer would have to reduce irrigated acres by 50%. Profitability of increasing the irrigation capacity by reducing irrigated acres increased net returns per irrigated acre by nearly 4 times. Even though only half of the acres are irrigated, profits would be greater than twice that of when irrigating the entire acreage.

IRRIGATION MANAGEMENT

In regions with allocation systems, irrigation management is critical to maximizing water inputs. As was discussed earlier, crops respond in a linear relationship to ET. However, each inch of irrigation does not return the same amount of grain yield as the previous inch of irrigation. Crops have critical time periods when water is more critical to the grain yield. Typically, that critical time period is during the reproductive growth stages of those crops. When restricted upon the total amount of water that can be applied, saving that water for the reproductive growth stages is the most advantageous. Grain yields are increased when water is properly timed and applied during the reproductive growth stages.

Corn

Corn has a greater response to water when irrigated during the reproductive growth stages, prior to tassel emergence to milk growth stages as compared to the vegetative growth stages and late grain fill. Barrett and Skogerboe (1978) found that corn yielded more when irrigated during the late vegetative and pollination growth stages as compared to irrigating during the vegetative or late grain fill growth stages in Colorado. In Kansas, Stone et al. (1978) found that irrigating during the silk emergence growth stage resulted in more grain yield than either prior to tassel or blister growth stages. If a single irrigation was to be applied, the blister growth stage had the lowest yield of the three time periods. Irrigating during each of the three growth stages did increase grain yields compared to a single irrigation.

Lamm (1989) found that when the total amount of water was restricted to less than adequate amounts for full irrigation, restricting the amount of water applied during the vegetative growth stage and conserving that water for the reproductive growth stage was advantageous for grain yields. Lamm also found that in years without severe water stress during the vegetative growth stages, limiting irrigation amounts during the vegetative growth stage and full irrigating during the reproductive growth stage conserved water (4-5 inches) with a small reduction in net returns ($11 – 22/acre) as compared to full irrigation management.

Soybean

Research with soybean have shown that irrigation during the vegetative growth stages can typically be reduced without significant reductions in grain yields and have a significant savings in water. Klocke et al. (1989) found that withholding irrigation during the vegetative growth stage for soybean resulted in little if no yield loss. However, as precipitation and/or soil water holding capacity decreased, irrigation was generally recommended to begin earlier in the reproductive growth stages. Irrigation should begin during the flower growth stage in western Nebraska on a sandy soil as compared to the pod elongation growth stage on silt loam soils.

Lamm (1989) found that reducing irrigation during the vegetative growth stages resulted in equal soybean yields as compared to full irrigation during years with normal precipitation. Reducing irrigation to 50% of ET during the vegetative growth stage and full irrigating during the reproductive growth stage reduced the amount of water applied by 22% (2.9 inches). However, in years when severe water stress occurs in the vegetative growth stages, grain yields for reduced irrigation during the vegetative growth stage were less than that of full irrigation.

Pre-Irrigation

Although there may be years that pre-irrigation is needed to refill the soil profile to field capacity, the efficiency of pre-irrigations is low. Lamm and Rogers (1985) found that the storage efficiency of non-growing season precipitation was reduced as the fall available soil water content was closer to field capacity. Although pre-irrigation may be needed in years with low precipitation, decisions on irrigating are better made in the spring as to take advantage of non-growing season precipitation. As was indicated by Nielsen (1998), the use of standing stubble increased the storage efficiency of off-season precipitation. Lamm and Rogers study was clean tilled so storage efficiencies were less than what may be expected with undisturbed fields.

ECONOMICS OF LIMITED IRRIGATION

Full irrigation management has the greatest return per acre when water (capacity or allocation) is not limiting (Lamm 1989). However, when system capacities or allocations are limiting, reducing irrigated acres and full irrigation management of a single crop is generally not the most optimum choice. A producer must determine what the difference in economic returns are when adding irrigated acres of a low water use crop at lower than optimum water levels as compared to reducing irrigated acres of a high water use crop such as corn. Crops such as soybean and wheat have greater net returns at lower amounts of irrigation as compared to corn. Schneekloth et al. (1995) found that net returns were greater when a three-year rotation of corn-soybean-wheat was irrigated with a 6 acre-inch/acre/year allocation as compared to a continuous corn rotation. This was due to the increase in corn grain yields following wheat and the inclusion of lower water use crops such as soybean and wheat which had yields that were closer to fully irrigated grain yields as compared to corn. They also found that the variability in net returns was also reduced with a three-year rotation as compared to continuous corn. Part of this reduction in variability was due to less variability in grain yields with the three-year rotation as compared to continuous corn.

As the allocations are reduced, the choice becomes do I further reduce the amount of irrigation on corn and further reduce yields or do I add a lower water use crop with less water applied in return for applying more water on corn? Schneekloth et al. (2001) found that cropping patterns switched to include lower water use crops such as soybean or wheat as the amount of water that could be pumped was reduced. As the amount of allocation is reduced, irrigation of corn is reduced to slightly less than that of optimum with little reduction in grain yield and net return. Schneekloth found that irrigated acres of lower water use crops do increase in favor of applying more water on fewer acres of corn to maximize the net return. However, as the amount of water is reduced further, irrigated corn generally is eliminated from the rotation. When allocations were reduced to 4 inches per acre, corn was no longer as profitable as compared to irrigating soybean or wheat.

Demonstration Project

Beginning in 1996, Schneekloth and Norton (2001) initiated an irrigation demonstration project. The demonstration project was located on farmer's fields throughout southwestern Nebraska on varying soil types and production systems. The purpose of this demonstration project was to educate producers on best management practices (BMP's) and limited irrigation management techniques that were developed for irrigated corn. Management practices that were demonstrated included current farmer management (Farm), BMP, beginning irrigation during the reproductive growth stage (LATE) and a strict allocation of 6 to 10 acre-inches/acre. Although yields were generally less for Late than compared to FARM or BMP, the net return was only slightly reduced and in some instances greater (Table 1). The greatest differences in net returns were on soils with lower water holding capacities such as at Elsie and Dickens. The water savings for LATE management was approximately 30% less than current farmer management. General comments by the cooperators were that they would be able to live with less water and that yields with less water managed properly were more than expected.

Table 1. Average Four-Year Net Returns[1] by Management Strategy and Site.

Site	FARM	BMP	LATE	ALLOC
	Management Strategy			
		Net Return ($/acre)		
Arapahoe	$186.69	$191.70	$212.69	$200.86
Elsie	$193.55	$193.92	$184.68	$153.86
Dickens[2]	$196.30	$198.09	$163.08	$161.57
Benkelman[3]	$193.52	$209.61	$194.15	$199.15
All Sites	$191.95	$195.53	$191.66	$173.73

[1]Net returns to land, labor, and management using 1999 average regional operating costs; assumes price of corn is $2.00/bu and pump cost is $2.50/acre-inch.
[2]Data for Dickens in 1997 not included due to irrigation error.
[3]Only 1999 data used for Benkelman site.

CONCLUSIONS

Fully irrigated crop production has greater returns per acre as compared to limited irrigation management. However, when limited on the amount of water that can be pumped, changes in agronomic and irrigation management practices can improve net returns. Changes in agronomic practices such as no-till can improve reduce water needs and increase the capture and utilization of precipitation. Changes may include adding lower water requirement crops that also have different critical times for water. Use of crop rotations can extend the irrigation season and allow for longer operation of irrigation systems with proper irrigation management. Adding different crops reduces the irrigated acres of any one crop. This allows for producers with low capacity systems to effectively manage the irrigation. Since fewer acres are irrigated at any one point in time, the ability of that system to meet ET needs of that crop improve. These management changes can improve yields and stretch limited water supplies.

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LIVING WITH LIMITED WATER
SUNFLOWERS AND COTTON AS ALTERNATIVE CROPS

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INTRODUCTION

The extreme heat and drought of 2002 in western Kansas resulted in many disappointing yields and too many outright crop failures in irrigated fields. Many areas in the central great plains experienced the driest year in the last 50 to 100 years, depending on location. Compounding the effect, temperatures were above normal for most of the growing season, particularly so in the first half of the season. Along with drought effects, the above average temperatures during pollination in many corn fields resulted in pollination failure in hybrids that had not previously experienced such problems. While one extreme year does not signal the end of irrigated corn production, prudent producers will adjust their management and repair inefficient sprinkler systems to lessen financial risk if the drought continues. Such steps should enhance profitability in average precipitation years and conserve irrigation water.

This paper reports two years irrigated sunflower (*Helianthus annus*) research with limited amounts of water in northwestern Kansas and to a lesser degree, will discuss irrigated cotton (*Gossypium hirsuitum* L.) production in the southern half of Kansas under limited water conditions. Low capacity irrigation wells, i.e. less than 350 gallon per minute, are becoming more common in western Kansas. These wells typically do not supply enough water to economically produce a full circle of corn. However, these wells are quite adequate for sunflower production. A cooperative field study was conducted in eastern Sherman county, KS in 2001. A replicated plot at the Colby research station was utilized to test water response of semi-dwarf versus standard height hybrids in 2002.

MATERIALS and METHODS, 2001

Plots were established under center pivot irrigation in a producer-cooperator's field approximately eight miles northwest of Brewster, KS. The irrigation treatments consisted of rain-fed dryland or limited irrigation consisting of irrigation for stand establishment, followed by one inch of water each two weeks for a month, then one inch of water per week until growth stage R5, no irrigation during bloom, then one inch of water at R6 and one more at R7. Plots were 10 by 30 feet with four replications in a randomized design. Triumph 545 sunflowers were seeded on May 29, 2001 at a final population of 21,000 plants/a. Weed control was accomplished by cultivation prior to planting and a PPE application of pendimethalin and sulfentrazone. The soil was a Keith silt loam (pH 7.7, O.M.

1.1) with a water holding capacity of approximately 2 inches per foot. Stand counts were made on June 27 and 17.5 feet of one row was hand harvested in each replicate on Oct. 12 and threshed in a stationary threshing unit approximately one week later.

RESULTS and DISCUSSION

Sunflower populations were uniform across all irrigation treatments. Head diameter on the irrigated plots ranged from 6.5 to 8.5 inches while dryland head diameter ranged from 3.5 to 5.5 inches. Precipitation from May 1 through harvest was 10.85 in., which produced 1510 lb./a average dryland yield, while the average irrigated sunflower yield was 2780 lb./a with 8.35 in. of additional water. The limited irrigation yielded 152 lb./a for each inch of irrigation which is in close agreement with work done by David Nielsen and others at the USDA ARS unit at Akron, CO. Irrigated replication 2 yielded only 2490 lb/a due to non-uniform plant spacing (bunching and skips) even though the population was 21,000 plants/a. The remaining three irrigated replications averaged 2880 lb/a, which underscores the need for uniform plant spacing and emergence. Test weight was 28.85 lb./bu for dryland and 31.9 lb./bu for irrigated treatments. Oil content was 51.2 % in dryland and 44.75 % in irrigated treatments. Gross returns, based on a $9.80/cwt cash price plus premium for oil content, were $162.02/a for dryland and $298.29/a for irrigation.

CONCLUSION

The dryland yield in this plot was about 200 to 300 lb./a more than average in the area this year, which would indicate that the amount and timing of rainfall was quite beneficial to yield and oil content. Irrigation increased yield by 152 lb./a per inch of irrigation. Oil content is believed to be the last component developed during seed fill and the lower oil content of irrigated sunflowers relative to dryland prompts the speculation that one more watering at R8 might have increased oil content as well as yield. Plans for 2002 include adding sites at the NWREC in Colby and west of Goodland with expanded irrigation treatments and population treatments, and with more and better observations.

Table 1. Seasonal precipitation for eastern Sherman county, KS

month	May	June	July	Aug.	Sept.	Oct.	Total
2001	3.35*	0.5	3.0	1.5	2.0	0.5	10.85

*2.35 received prior to May 10.

Table 2. Date and amount of irrigation for eastern Sherman co. KS, 2001.

Date	5/31	6/6	6/20	7/5	7/12	7/19	7/26	8/10	8/16	Total
Amount(in.)	0.6	0.75	1.0	1.0	1.0	1.0	1.0	1.0	1.0	8.35

Table 3.
Effect of Irrigation on sunflower yield components at eastern Sherman co. KS.

Treatment	Head dia.[1]	Test wt.	Yield	Oil	Gross Return[2]
	Range (in.)	Lb./bu	lb./A	%	$/A
Dryland(avg)	**3.5-5.5**	**28.85**	**1510**	**51.2**	**162.02**
rep 1		28.5	1570	51.0	
rep 2		28.7	1520	51.2	
rep 3		29.1	1530	51.5	
rep 4		29.1	1430	52.3	
Irrigated(avg)	**6.5-8.5**	**31.9**	**2780**	**44.75**	**298.29**
rep1		32.4	2920	45.1	
rep 2		31.5	2490	45.4	
rep 3		31.0	2900	43.7	
rep 4		32.6	2840	44.8	

[1] Range in diameter in inches of 10 consecutive heads at a random location in plot.
[2] Base price of $9.80/cwt + oil premium of 2% price increase/each 1% oil above 40%.

MATERIALS and METHODS, 2002

Plots were established with surface line source irrigation (soaker hose) at the Northwest Research and Extension center at Colby, KS. The plots were established in a growing, dryland wheat crop which was terminated on 15 May 2002 by glyphosate herbicide application. All plots received a 1.5 in. irrigation on 18 June and 5 July to insure adequate moisture for germination and establishment. Thereafter, control treatments were rain-fed dryland while the limited irrigation treatments were scheduled to maintain soil water content above 40 % using the KanSched irrigation scheduling software (Kansas State University) and data from the weather station on the Colby research station. Two identical irrigated treatments were maintained until 3 Sept. when the late irrigation treatment was given 1in. more water. Triumph 545A (standard height) and Triumph 567DW (semi-dwarf) sunflowers were seeded on 18 June, 2002 at a final population of 17,500 plants/a. This was less than desired (24,000plants/a) due to extreme drought and grasshopper pressure. Weed control was accomplished by a PPE application of pendimethalin (32 oz/a) and sulfentrazone (3 oz/a) and hand hoeing. The soil was a Keith silt loam (pH 7.7, O.M. 1.1) with an available water holding capacity of approximately 2 inches per foot. Stand counts were made on 2 July and 17.5 feet of two rows were hand harvested in each replicate on 24 Sept. and threshed in a stationary threshing unit approximately two weeks later.

RESULTS and DISCUSSION

Sunflower populations were uniform across all irrigation treatments, but had uneven spacing between plants characterized by four to five 2 ft. skips per 100 ft. of row. Head diameter on the irrigated plots ranged from 6.5 to 8.5 in. for 545A and 8 to 9 in. for 567DW while dryland head diameter ranged from 3.5 to 5.5 inches. Precipitation from 12 May through harvest (24 Sept.) was 9.39 in. When combined with 3.0 in. of irrigation the dryland control plots averaged 708 lb./a (545A) and 1719 lb/a (567DW). The early termination (R-7) treatment produced 1205 lb./a (545A) and 2356 lb/a (567DW) with 9.6 in. of irrigation plus 9.39 in. rainfall. The late termination (R-8) treatment produced 1530 lb/a (545A) and 2515 lb/a (567DW) with 10.6 in. irrigation and 9.39 in, rainfall. The cumulative Evapo-Transpiration(ET) for this crop location was calculated by KanSched software (KSU) as 28.84 in. which leaves a 8.6 to 9.7 in. moisture deficit. The soil at planting time was too dry to allow penetration of a steel rod probe. The soil moisture content prior to irrigation is assumed to near permanent wilting point within the top three feet of soil. After 3 in. of irrigation just after planting , which all plots received, the steel rod probe penetrated to a depth of 42 to 46 in. It is estimated that the soil profile from three to six ft. contained as much as three in. available water for crop growth. The 2002 growing season was about 5°F. hotter average and precipitation was 5 to 7 in. less than average. The plots were not sprayed for insect control. While head moth damage was slight, stem weevil, *Cylindrocopturus adspersus*(LeConte), and stem borer, *Dectes texanus* (leConte), pressure was heavy. Hybrid 545A had 25 % lodging and the majority of pith eaten away in the lower 2 ft. of stem. Hybrid 567DW had less than 5 % lodging and less than one ft. of the lower stem pith eaten. Recent research by Rob Aiken at Colby indicated that yields are reduced 600 to 1200 lb/a by not controlling stem pests. Notably, examination of 30 stems of each hybrid revealed no spotted stem weevil larvae in 567DW compared to about 25 per stem in 545A (data not shown). Soybean stem borer larvae were found in both hybrids equally. Hybrid 545A matured about 10 days earlier than 567DW, which may have been a result of the differences in stem weevil pressure. Also, deer and bird predation of 25% in 545A and 10% in 567DW was recorded. Again, the difference in maturity date could account for the predation difference. The lodging difference could be partially due to maturity, partially due to less insect damage to the interior of the stalk and partially due to less mechanical wind force on the shorter hybrid. Also, the stalk diameter of 567DW was slightly larger than that of 545A. Yields were adjusted to account for lodging and predation to show the true irrigation effect. Hybrid 545A's adjusted yields were 1259 lb/a dryland, 2143 lb/a early irrigation termination and 2720 late termination. Hybrid 567DW's adjusted yields were 2010 lb/a dryland, 2756 lb/a early irrigation termination and 2941 late termination. Hybrid 545A's oil content was 46.5 % in dryland and 46.0 % in irrigated treatments. Hybrid 567DW's oil content was 37.5 % in dryland and 36.6 % in irrigated treatments. It is speculated that decreasing soil water contents late in the season hurt the oil yield of 567DW to a greater degree due to its later maturity. Gross returns, based on a $12.75/cwt cash price(27 Nov. 02) plus premium for oil content, or on $13.50/cwt for bird seed quoted the same day are reported in table 4. These prices were higher than long-term averages, however 2003 NuSun contracts are available locally for $11.50/cwt. Seed yield response to irrigation is reported in Figure 1 and range from 125 lb/a in to 199 lb/a in., based on adjusted seed yield

CONCLUSION

The adjusted dryland yield of 545A was similar to the average yield in the KSU dryland sunflower variety plots, located less than a half mile away, while 567DW yielded about 200 lbs/A more than the best yielding hybrid in the KSU variety plots. Seed yield response to irrigation ranged from 125 to 153 lb/A in. for 545A and from 165 to 199 lb/A in. for 567DW, which is in agreement with other reports. The lower oil content of 567DW compared to 545A is assumed to be a result of the drought and heat stress of the year and/or possibly a characteristic of the particular hybrids. Hybrid 545A is known to be a high oil hybrid, frequently ranging from 45 to 50% oil. Hybrid 567DW is relatively new and does not have as many years data on oil content. The differences in lodging and as-harvested versus adjusted seed yields underscore the importance of controlling stem pests. It is not known whether hybrid 567DW has a physiological or morphological resistance to stem weevil and the observations of one site-year are not sufficient to draw conclusions, but it is a possibility that needs further investigation. Recent research (Charlet, et al., 2001) shows 600 to 1200 lb/a seed yield increase for one insecticide application to control stem pests. Part of that increase is due to decreased lodging, but part is due pre-mature death of plants caused by insect damage and associated diseases vectored by the insects. Thus, it is possible that the best adjusted yields reported in this study could have been 300 to 500 lb/a better with timely insect control. Seed yield was reduced by 450 lb/a due to less than desired population and skips and doubles in row in 2001, and could have been reduced for the same reason in this plot, but there was no control to aid documentation. The adjusted seed yields could have possibly been 600 to 1000 lb/a higher and such yields have been seen in 2001 and 2002 in the NWREC irrigated NuSun sunflower performance trials and other trials in the area. Plans for 2003 at the NWREC in Colby call for continued work comparing standard height and semi-dwarf (short statured) hybrids, and possibly adding one more irrigation treatment.

Table 1. Seasonal precipitation, irrigation and ET at NWREC, Colby, KS*

month	May	June	July	Aug.	Sept.	Total
Rain	1.31	1.26	1.49	4.17	1.16	9.39
Irrigation	0.00	1.50	1.50	6.60	1.10**	9.6/10.7**
Reference ET	5.48	10.8	10.91	9.00	5.73	41.92
Sunflower ET	1.24	6.05	10.26	8.13	2.15	27.83

*12 May, 2002 to 24 Sept., 2002
**Late irrigation treatment only

Table 2. Date and amount of irrigation at NWREC, Colby, KS, 2002.

Date	6/18	7/5	8/1	8/5	8/14	8/21	9/3**	Total
Amount(in.)	1.5	1.5	1.8	1.8	1.5	1.5	1.1**	9.6/10.7**

**Late irrigation treatment only

Table 3.
Effect of Irrigation on sunflower yield components at NWREC, Colby,. KS, 2002.

Treatment	Head dia.[1]	Yield	Oil	Income[2]	Adjusted yield[3]	Income
	Range (in.)	lb./A	%	$/A	lb/A	$/A
Dryland(avg)						
545A	3.5-5.5	708	46.5	102.00	1259	186.42
567DW	3.5-5.5	1719	37.5	232.07B	2010	271.35B
9.6" Irrigation(avg)						
545A	6.5-8.5	1205	45.8	171.46	2143	304.95
567DW	8 - 9	2356	37.3	318.06B	2756	372.06B
10.7" irrigation(avg)						
545A	6.5-8.5	1530	46.2	219.26	2720	392.50
567DW	8 - 9	2515	35.9	339.53B	2941	397.04B

[1] Range in diameter in inches of 10 consecutive heads at a random location in plot.
[2] Gross income based on cash price of $12.75/cwt (27 Nov., 2002) + oil premium of 2% price increase/each 1% oil above 40%, or bird seed price quote for the same time of $13.50/cwt denoted 'B', whichever produces the greatest gross income.
[3] Yield adjusted to compensate for lodging and predation to better evaluate effect of irrigation. Lodging was 25%(545A) or 5%(567DW) and predation was 25%(545A) and 10%(567DW).

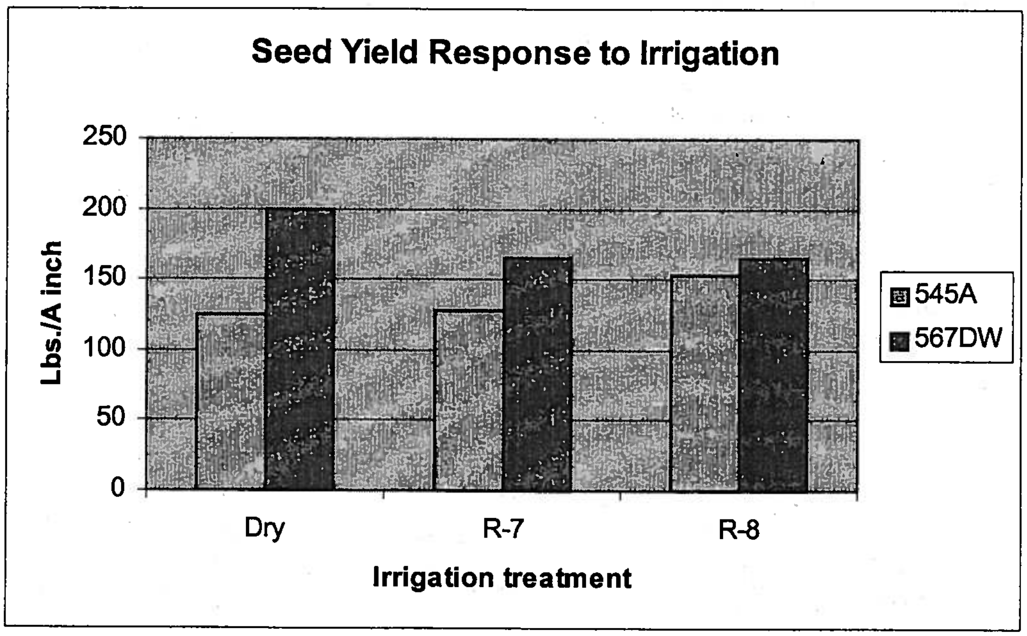

Fig. 1. Seed yield response to irrigation of two sunflower hybrids. Yield response values are based on adjusted seed yield and assume no water available in the top three feet of soil and 3 in. water available in the three to six foot deep profile and 5.3 in. water use to develop plant prior to seed development. All treatments received 9.39 in. rain from 12 May '02 until 24 Sept. '02 and 3.0 in. irrigation for stand establishment. Treatment R-7 received an additional 6.6 in. irrigation. Treatment R-8 received an additional 7.7 in. irrigation.

COTTON PRODUCTION IN KANSAS

Cotton production in Kansas is relatively new, having started in the early 1980's. The area of adaptation is roughly the southern half of the state, minus the higher altitude areas in western Kansas. Cotton production is possible in Kansas because of new, earlier maturing hybrids and growth regulators. Cotton is a perennial tropical plant that is grown like an annual crop in the southern great plains due to frost killing the plant in the fall. Cotton fiber is used in the textile industry, while the seed is sued for oil and livestock feed. Cotton is extremely sensitive to 2, 4-D and other growth regulator herbicides, as well as carryover residues from sulfonylurea and imidazolinone herbicides.

Optimum planting dates in Kansas range from May 1 to June 1, or when soil temperature is 60 °F. at the 8 in. depth for three consecutive days or more. Seeding rates for irrigation range from 65,000 to 85,000 per acre. Seed should be placed in moist soil, from 1 to 2 in. deep. Cotton will not tolerate crusting and will require rotary hoeing if crust develops. Planting seed should be treated with fungicide and insecticide to insure good stands. Weed control is necessary in early season growth because cotton is not very competitive during the first month and a half. Control of bur or sticker weeds in late season is important since these weeds interfere with harvest and ginning of the lint. Cotton grown in Kansas is harvested by stripper machines that remove all of the bolls at once. It is then packed in module builders at the field edge and transported to the gin on schedule. The gin removes the lint and seeds from the cotton bur (boll) and then removes the seed from the lint, which is baled into 500 lb. bales. The grower pays the ginning costs and sells the lint at a price determined by the grade, fiber length, color and cleanness of lint. Cotton prices generally range between 35 and 70 cents/lb.

Cotton has some similarities to soybeans, both crops abort half or more of their blooms and both crops continue to bloom until late in the season. Cotton will begin blooming about 30 days after emergence and it takes about 75 days for a boll to mature. Thus, it takes about 100 days for the plant to mature its first bolls. The length of growing season in Kansas is 120 to 140 days, making it critical to relieve stress during the first 30 days of bloom to decrease abortion during the early boll growth stages. Most bolls that set after the first 30 days of bloom will not mature before frost. Growth regulators are used to restrict vegetative growth and discourage late blooms. Using less water and resources for vegetative growth should help the plant partition more resources into reproductive growth. Cotton uses about 60 lb. of N per bale of production and about 30 lb of P_2O_5 . Excess nitrogen, especially early in the season, encourages excessive vegetative growth and lodging. Breakeven yields of cotton in Kansas are about 3/4 bale/a dryland and about 1.5 bales/a irrigated, depending on price and grade. Irrigated cotton yields of 1.5 to 2.5 bales/a have been reported in Kansas recently. But, like soybeans, cotton yields are dramatically affected by heat. While soybeans don't tolerate temperatures above 95 during seed fill very well, cotton needs warm, tropical temperatures throughout the first 100 days of growing season for efficient fruiting. In a cooler than average growing season, such as 1999, cotton will struggle to mature before frost, while soybeans will do well, but the 2002 growing season with its above average heat, favored cotton production, with many irrigated yields in excess of 2 bales/a being reported.

Irrigation scheduling for cotton should be similar to sunflower irrigation. Both crops need pre-watering if rainfall is not sufficient for germination and emergence. Normal rainfall is usually sufficient for vegetative growth in both crops. Excessive water during vegetative stages of both crops will encourage excessive stalk and foliage growth, possibly detracting from reproductive growth, i e. changing the harvest index. At the initiation of reproductive growth, both crops should be watered to maintain at least 50% available soil water content until near physiological maturity. Anecdotal accounts from producers, are indicating profitable production with 10 to 14 in. of irrigation, similar to sunflower. However, since sunflower is native to the great plains and does not abort blossoms, it is much more tolerant of slow irrigation or watering interrupted by mechanical difficulties than cotton. Cotton may experience cold shock from application of cold well water to plants on hot (≥100 °F.) days, although no literature was found to support that. Both crops share many similar requirements and offer profitable alternatives to Kansas and great plains producers.

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CROP WATER USE REQUIREMENTS and WATER USE EFFICIENCY

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EVAPOTRANSPIRATION (ET)

Evaporation (from soil or water surfaces) and transpiration (from plant surfaces) require that water be converted from liquid to vapor. Heat (energy) is required to vaporize the liquid. The vaporization of water is influenced by: 1) Amount of energy at the vaporization surface, 2) Extent and nature of the vaporization surface, and 3) Water supply at the vaporization surface.

Energy used in evapotranspiration (ET) comes from two sources: 1) The sun (solar radiation) and 2) The horizontal movement of warm and dry air masses (advection). Reference (Potential) ET is estimated by using weather data, and establishes the evaporative demand or evaporative potential of the atmosphere for a stated reference crop. In the western US, alfalfa is the most common reference crop. In Europe, well-maintained, irrigated grass is typically the reference crop. The alfalfa reference crop is about 18 inches tall, actively growing with no water stress conditions, and with relatively little soil surface evaporation (a relatively dry soil surface). The Penman and Jensen-Haise equations, with alfalfa the reference crop, are two of many such equations for estimating Reference ET by using weather data.

Calculated Reference ET is then adjusted for crop conditions through use of an ET crop coefficient curve (ratio of actual crop ET to reference crop ET). Conditions of growth pattern, crop architecture, and leaf surface area influence the ET coefficient curve of crops. Each crop has its own unique ET coefficient curve. An ET coefficient curve for corn is presented in Figure 1, with reference ET calculated by the Jensen-Haise equation (alfalfa the reference crop). In this example (Figure 1), advance through the corn growing season is on the basis of fraction of thermal units.

Calculated Reference ET is further adjusted for conditions of soil water availability. Actual crop ET is at the maximum of crop adjusted-Reference ET when soil water is readily available. As soil water becomes less available, actual crop ET reduces in comparison to crop adjusted-Reference ET. Therefore, the downward adjustment of ET because of water stress conditions is a more pertinent consideration in dryland and limited irrigation environments than with full irrigation. This reduction is accounted for through use of the available soil water coefficient (water stress factor). There are several ways of expressing the water stress factor, with the logarithm reduction method (presented in Figure 2) the most common.

Therefore,

Actual crop ET = Reference crop ET x Crop ET coefficient x Soil water stress factor

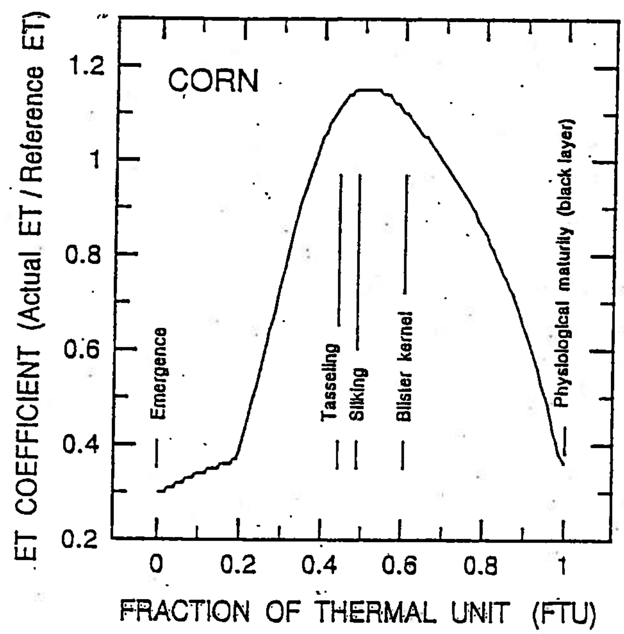


Figure 1. ET crop coefficient curve for corn (ratio of field-measured ET to Jensen-Haise reference ET on the vertical axis vs. fraction of thermal units on the horizontal axis).

With ET being an energy-driven process, energy levels cap the possible crop ET for an individual day at about 0.50 to 0.55 inches. For time intervals of about 1 week, average daily ET will max out in the range of 0.30 to 0.33 inches/day for corn, sorghum, soybean, and wheat; whereas sunflower will max out at about 0.38 inches/day (Hattendorf et al., 1988).

A typical pattern of ET during the corn growing season is illustrated in Figure 3. Measured ET is on the vertical axis (in inches/day on the right-side axis) and fraction of thermal units on the horizontal axis. These data were collected near Scandia, KS (Gordon et al., 1995). Data points are for measurement intervals of about 1 week and data were collected over several growing seasons.

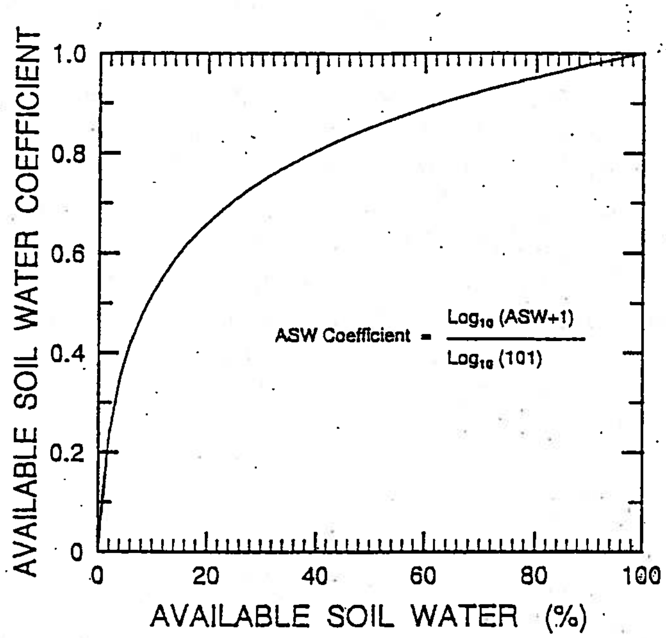


Figure 2. Illustration of the logarithm reduction method used to reduce actual crop water use (ET) estimates based on water stress levels. The soil water stress factor (available soil water coefficient) is on the vertical axis and the percent of available soil water is on the horizontal axis.

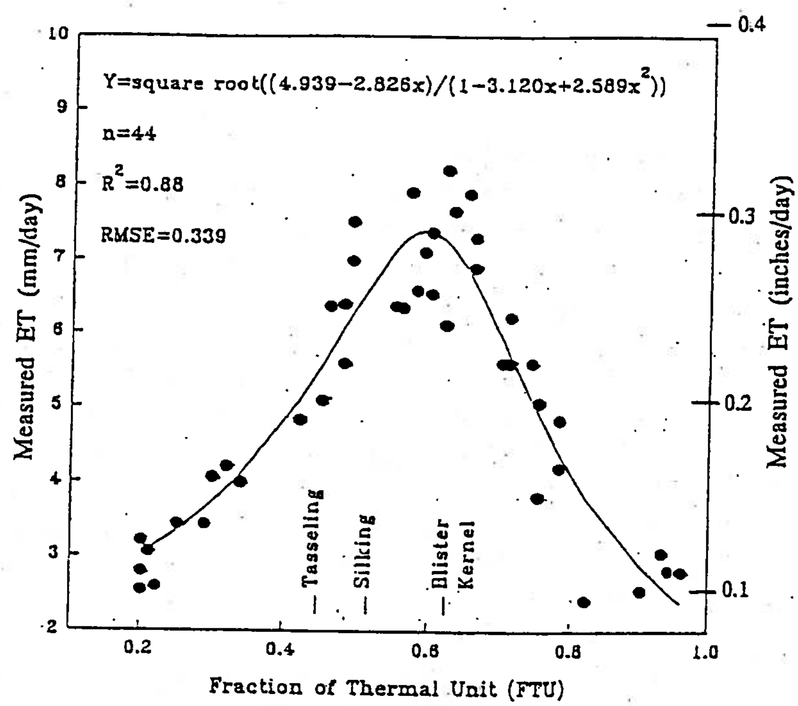
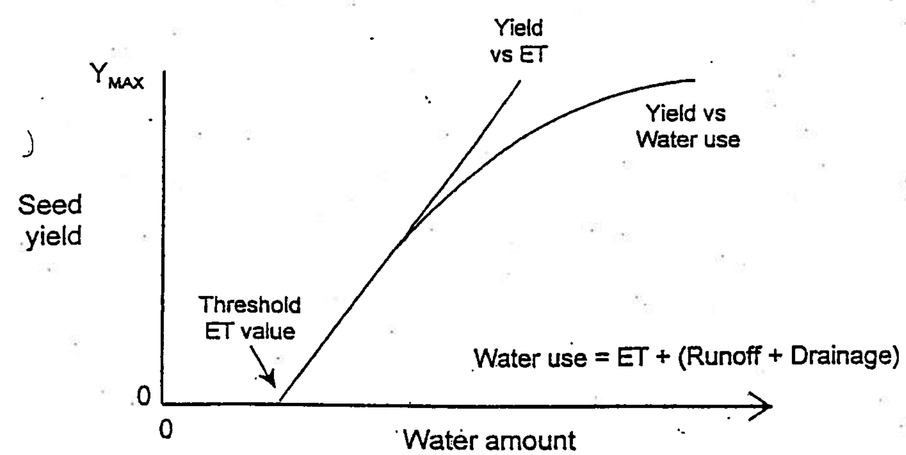


Figure 3. Measured evapotranspiration (ET) of corn vs. fraction of thermal units, 1984-1991, Scandia, KS.

CROP YIELD versus ET RELATIONSHIPS

The diagram immediately below illustrates the general relationships between seed yield and water amount (ET or water use). As used here, ET refers to evapotranspiration while water use refers to ET plus losses by runoff and internal drainage from the soil profile. Seed yield vs. ET is a linear relationship, although variability can and does exist. Seed yield vs. water use (ET + Runoff + Drainage) is typically a curvilinear relationship. The seed yield vs. ET relationship is more transferable among geographic locations than is the seed yield vs. water use relationship that is more influenced by soil and landform characteristics that influence runoff and drainage.



The following table lists values of "Threshold ET", "Maximum ET for a typical full-season variety", "Slope of seed yield vs. ET", and "Slope of long-term seed yield vs. ET" for five crops from research in western Kansas by Stone et al. (1995) and Khan (1996). "Threshold ET" is the ET necessary to move into the seed producing segment of the yield vs. ET relationship. That is, at the "Threshold ET" value and below, seed yield is zero. "Maximum ET" gives the upper value of ET expected for full-season varieties with good water conditions (no water stress). The "Slope of yield vs. ET" gives the seed yield increase per inch of ET in the seed producing segment of yield vs. ET. This would be the expected yield increase due to water (ET) in a year with no out-of-the-ordinary yield reducing factor such as hail, frost, insects, etc. Because out-of-the-ordinary yield reducing events do occur, the "Slope of long-term yield vs. ET" is less than the yield vs. ET slope for an individual good year.

The "Threshold ET" value is of critical importance in assessing if seed yield will likely be obtained in drier crop environments. Within the four summer row crops of the following table, "Threshold ET" is 5.4 inches for sunflower, 6.9

inches for sorghum, 9.0 inches for soybean, and 10.9 inches for corn. The water stress sensitivity of growth stages of various crops is also important in assessing their suitability for drier environments. The "Slope of yield vs. ET" is important in assessing the response of crops to irrigation that is converted into ET. Within the four summer row crops of the table below, yield response per inch of ET is 218 lb/acre/inch for sunflower, 330 lb/acre/inch for soybean, 683 lb/acre/inch for sorghum, and 946 lb/acre/inch for corn.

Crop	Max. ET for full-season variety	Threshold ET	Slope of yield vs. ET	Slope of long-term yield vs. ET *
Corn	25 inches	10.9 inches	16.9 $\frac{bu/acre}{inch}$	13.3 $\frac{bu/acre}{inch}$
Grain sorghum	21 inches	6.9 inches	12.2 $\frac{bu/acre}{inch}$	9.4 $\frac{bu/acre}{inch}$
Sunflower	22 inches	5.4 inches	218 $\frac{lb/acre}{inch}$	150 $\frac{lb/acre}{inch}$
Winter wheat	24 inches	10.0 inches	6.0 $\frac{bu/acre}{inch}$	4.6 $\frac{bu/acre}{inch}$
Soybean	24 inches	9.0 inches	5.5 $\frac{bu/acre}{inch}$	4.5 $\frac{bu/acre}{inch}$

* Long-term (multi-year) slope is less than full slope due to yield reducing factors such as water stress, hail, frost, insects, etc.

YIELD RESPONSE TO WATER (STRESS FACTORS)

The following table gives the relative yield response (decrease) per unit of ET deficit (water deficit) during growth periods of five crops. The values should be compared within a crop to get the relative weighting of water stress sensitivity of various growth periods for the individual crop. That is, within corn, an inch of ET deficit during flowering decreases grain yield 3.8 times as much as an inch of ET deficit during the vegetative growth stage (0.53/0.14 = 3.8). Within grain sorghum, an inch of ET deficit during flowering decreases grain yield 2.0 times as much as an inch of ET deficit during the vegetative stage (0.42/0.21 = 2.0). Along with the sensitivity to water stress in corn being greatest during flowering, daily water use is greatest during flowering through about the milky-fluid growth stage (Figure 3). These two factors working together produce the need for water in corn during flowering.

Relative yield response per unit of ET (within a crop) to water deficit during selected growth periods.

Crop	Growth period			
	Vegetative	Flowering	Yield formation	Ripening
Corn	0.14	0.53	0.19	0.14
Grain sorghum	0.21	0.42	0.21	0.16
Sunflower	0.25	0.42	0.27	0.06
Winter wheat	0.19	0.51	0.25	0.05
Soybean	0.10	0.40	0.50	—

The relative weighting of water stress sensitivity within a crop is illustrated in the previous table. Those relative weightings of water sensitivity give insight into the growth periods of most critical water need for those five crops. On average, rainfall during the most sensitive growth periods will give the greatest yield benefit. Also, limited irrigation should be timed to avoid water stress at the most sensitive growth stages. On average, that will give the greatest yield benefit from a limited water resource. The timing of limited irrigation for maximum seed yield benefit (on average) is given in the table below.

Timing of limited irrigation for maximum seed yield benefit.

Crop	Initiation of limited irrigation....	To avoid (lessen) water stress particularly during
Corn	Near (prior) or at tasseling	Silking
Grain sorghum	Head extension	Flowering
Sunflower	Head development	Disk flowering
Winter wheat	Head extension	Flowering
Soybean	Mid to late pod set	Early to mid bean fill

A consideration of the suitability of crops for rainfed-only management in drier environments starts with an examination of the "Threshold ET" and water stress sensitivity values. The suitability of crops for limited irrigation management in drier environments is influenced by the factors of "Threshold ET" , water stress sensitivity, and crop response to added water ("Slope of yield vs. ET"). The suitability of crops for full irrigation management in drier environments is primarily driven by the crop yield response to water ("Slope of yield vs. ET").

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Water Savings from Crop Residue in Irrigated Corn

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Introduction

During the past 10-15 years, there has been a great deal of emphasis in sprinkler applications to move closer to the target. The thinking has been to decrease the exposure to potential evaporation in the air. At the same time sprinkler manufacturers have produced heads with lower operating pressures producing fewer fine spray particles leaving far fewer particles subject to evaporation. The result is that application efficiencies have improved.

What remains are the same wet soil surfaces beneath the crop canopies. We need to spread the water to gain infiltration, but then evaporation from the soil surface takes over after irrigation stops. It has been assumed that evaporation from the soil surface in irrigated crop canopies is relatively small. The objective of this paper is to report on some of the research in the area of evaporation from soil surfaces.

Evaporation-Transpiration Partition

Transpiration, or the process of water evaporating near the leaf and stem surfaces, is a necessary function for plant life. It is literally the final driving force for water flow through the plant. It provides plant cooling. Transpiration relates directly to grain yield in the crops we produce. Transpiration rates are driven by atmospheric conditions and by the crop's growth stage. As a crop grows it requires more water until it matures and generally reaches a plateau. Daily weather demands cause fluctuations in transpiration as a result. Soil water begins to limit transpiration when the soil dries below a threshold generally half way between field capacity and wilting point. Irrigation management usually calls for scheduling to avoid water stress.

Evaporation from the soil surface may have some 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. Independent measurements are becoming more important as we strive to tighten management of sprinkler irrigation to achieve more efficient water use.

Field research has shown that in sprinkler irrigated corn as much as 30% of total evapotranspiration is consumed as evaporation from the soil surface (Klocke et. al., 1985). These results were from bare soil conditions for sandy soils with sprinkler irrigation. 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 in (12 mm) for sandy soils and 0.4 in (10.2 mm) 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 then soil limited evaporation is reached, evaporation is controlled by how fast water and water vapor can move through the soil to the soil surface. The relationships that have been developed to describe soil limited evaporation are shown in Fig 1 for a silt loam soil. 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.

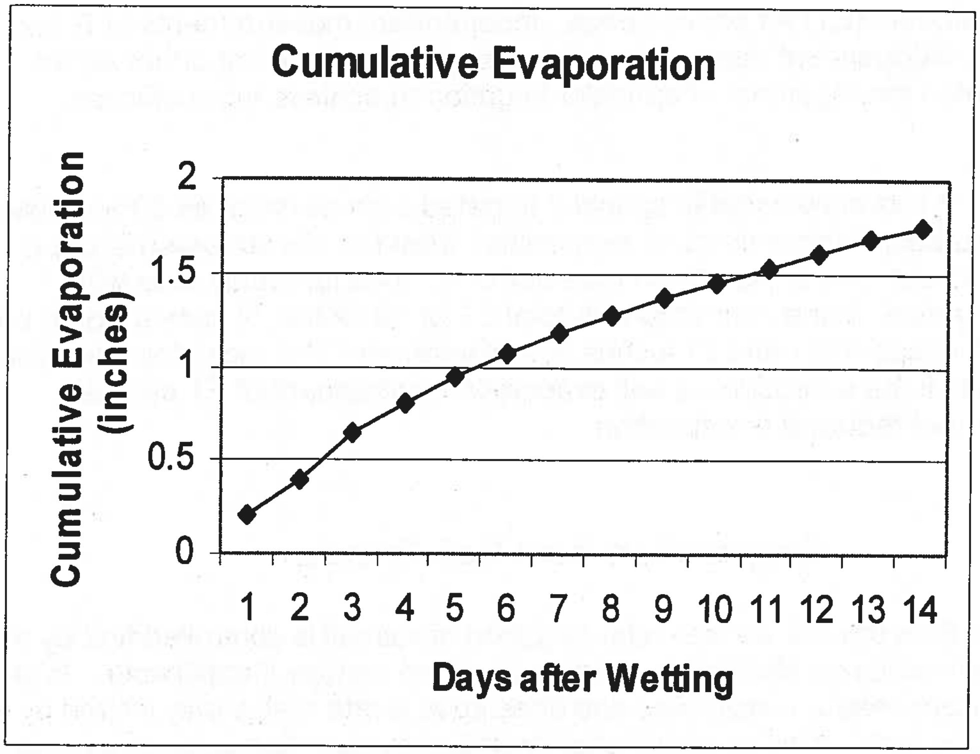

Fig.1. Soil limited evaporation after day 2 as described by E = C*t^-1/2.

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. 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 20-25 bushels in the corn crop. This difference came from the presence of standing wheat stubble during the fallow period versus bare ground.

The question is to what extent water savings could be realized from crop residue management in sprinkler irrigation. A research project was conducted 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. Increases in soil water over time due to elimination of root extraction in the lysimeters were compensated with a procedure of switching a duplicate set of lysimeters immediately after each irrigation or significant rainfall. When a set of lysimeters was not in field use it was dried and brought to field soil water content immediately before replacement in the field.

Half of the lysimeter treatments were bare and half were covered with flat wheat straw 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. One treatment was dryland, receiving no irrigation. The next treatment was limited irrigation, receiving three irrigation events, one during vegetative growth, one during flowering, and one during grain filling. The last irrigation treatment was full irrigation with nine irrigation events. The first seven irrigations were delivered at week intervals and the last two and approximately two week intervals. 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 of the field study conducted near North Platte Nebraska are in Figures 2 and 3. The soil for the study was a silt loam. The first striking result was in the dryland treatment. The unshaded bare and straw covered lysimeters nearly tracked each other for daily evaporation. There were only six rainfall events that measured over 0.4 in (10 mm) of precipitation. The pattern of cumulative evaporation for the bare dryland treatment indicates brief periods of energy limited evaporation. This indication is more subtle for the straw covered treatment. Even more interesting is that the straw mulched treatment has the same evaporation as the bare treatment for dryland management under the crop canopy. The straw mulch did not play an additional role in reducing the energy limited evaporation beyond the roll of the crop canopy.

For limited irrigation, three irrigation events were added, 2.0, 2.0, and 1.75 in. depths. 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

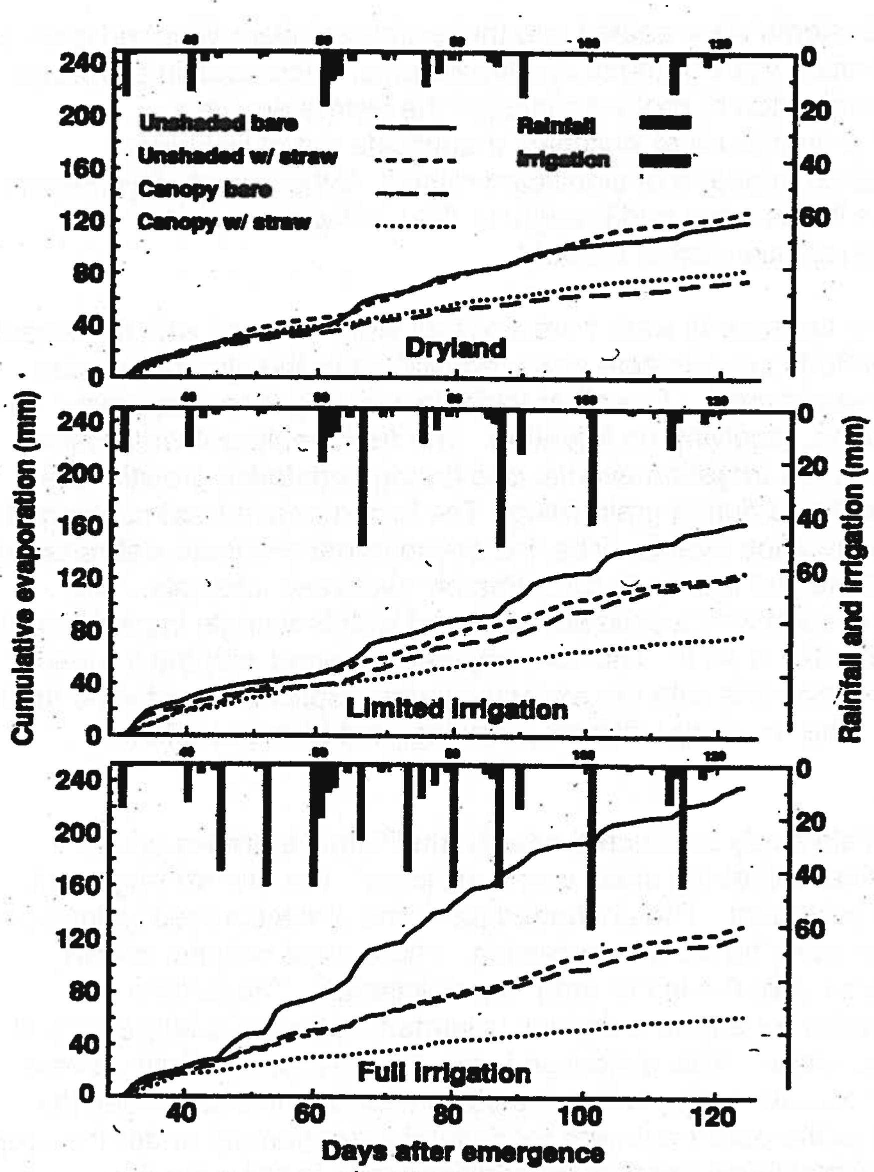

Fig. 2. Cumulative evaporation for dryland. limited irrigation, and full irrigation management. (Todd et, al., 1991)

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.

Full irrigation included nine irrigation events, seven of which were at weekly intervals and two 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 are more subtle early in the bare soil treatment under the crop canopy. The magnitude of unshaded bare soil

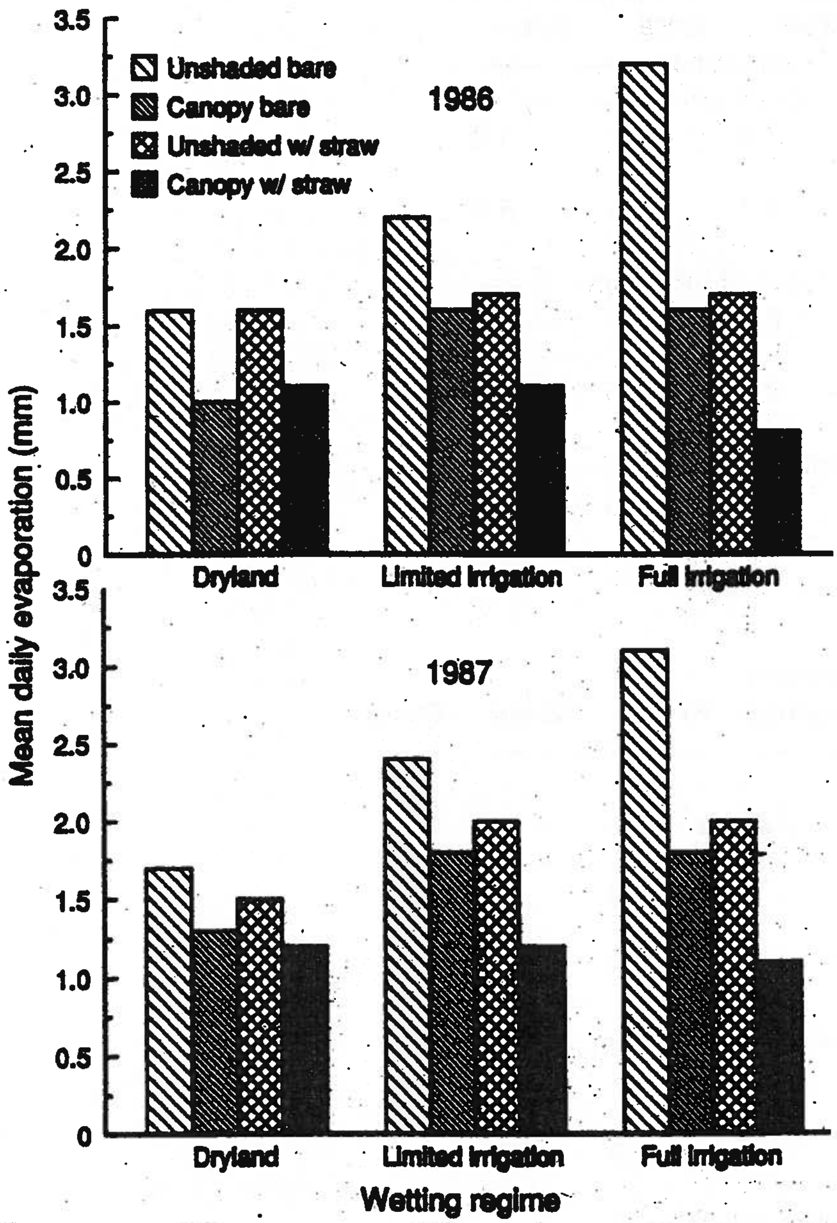

Fig. 3. Mean daily evaporation for dryland, limited irrigation, and full irrigation management. (Todd et. al., 1991)

evaporation is far greater in the fully irrigated treatment, but the unshaded mulched and bare soil evaporation under the canopy is similar to the limited values. These latter two treatments also track each other closely as they did in they limited management. The mulching effect was even greater in the fully irrigated management than the limited and dryland management. This effect started early and carried on throughout the growing season.

Table 1. Full growing season evaporation including irrigation and rainfall days.

Year	---Unshaded------ Bare	Straw	---Shaded------- Bare	Straw
	------------------in/season		---------------	
	----------------Dryland		------------------	
1986	7.6	7.6	4.7	5.2
1987	8.0	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

Table 2. Full Water Season Savings From Straw Cover.

Year	---Unshaded-----	----Shaded------
	---------------in/season	-----------------
	-------------------Dryland	----------------
1986	0.0	0.0
1987	0.9	0.5
	--------------Limited Irrigation	---------
1986	1.9	2.4
1987	1.9	2.8
	--------------Full Irrigation	--------------
1986	6.6	3.8
1987	5.2	3.8

Full Season Results

Cumulative evaporation results in figure 2 do not include days with occurrences of irrigation or rainfall. Measurements were not taken on these days. 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. The results are shown in Table 1. These evaporation values may still be conservative since evaporation rates are highest immediately after wetting. The potential full season reduction in evaporation by the wheat straw cover is then shown in table 2.

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 soil. It has also been demonstrated that crop residues, in this case wheat straw lying flat, can reduce in half the evaporation from soil 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 2.5-3.5 inch savings in water due to the wheat straw during the growing season. Dryland research would suggest that stubble is worth at least 2 inches in 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 at least 60 bushels of corn. During 2002, many irrigators in the Central Plains could have used an extra 5 inches of water.

One of the challenges is to determine if other residues are as good as flat wheat straw in reducing evaporation. The flat wheat straw provided a compete mat, but it also retained moisture itself. Would other residues like untilled corn stalks or soybean stubble or standing wheat straw do as well or better?

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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.

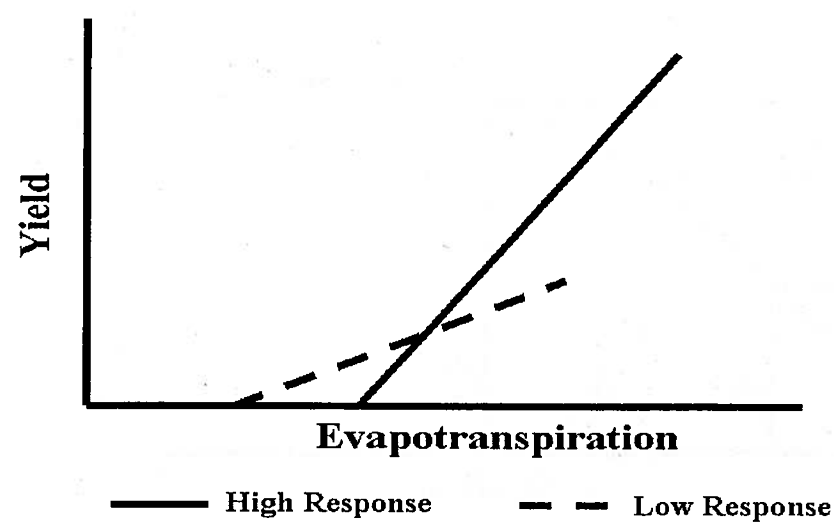

Figure 1. Generalized Yield vs Evapotranspiration response for high response crop and low response crop.

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.

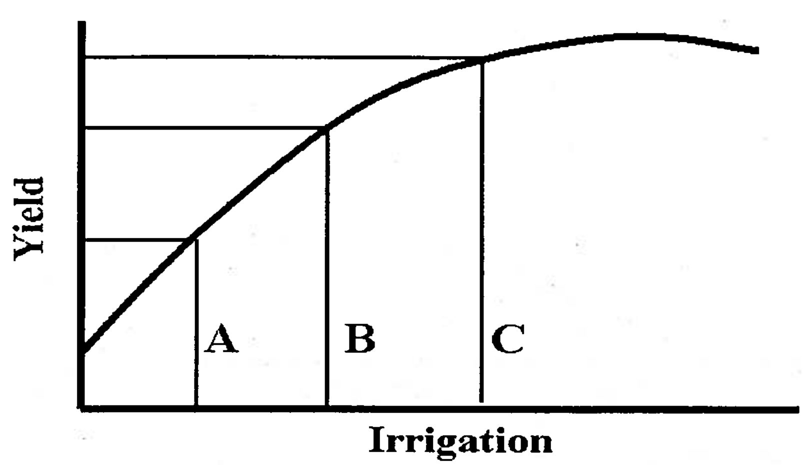

Figure 2. General Yield vs Irrigation Response.

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.

CORN PRODUCTION IN THE CENTRAL GREAT PLAINS 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. Corn is the major irrigated crop in the region and is very responsive to irrigation, both positively when sufficient and negatively when insufficient. This paper will discuss the nature of corn evapotranspiration rates and the effect of irrigation system capacity on corn production and economic profitability. Although the information presented here is based on information 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 corn production.

CORN EVAPOTRANSPIRATION RATES

Corn evapotranspiration (ET) rates vary throughout the summer reaching peak values during the months of July and August in the Central Great Plains. Long term (1972-2002) 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 0.266 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 2002 were 0.331 and 0.263 inches/day, respectively, representing an approximately 15% increase over 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.

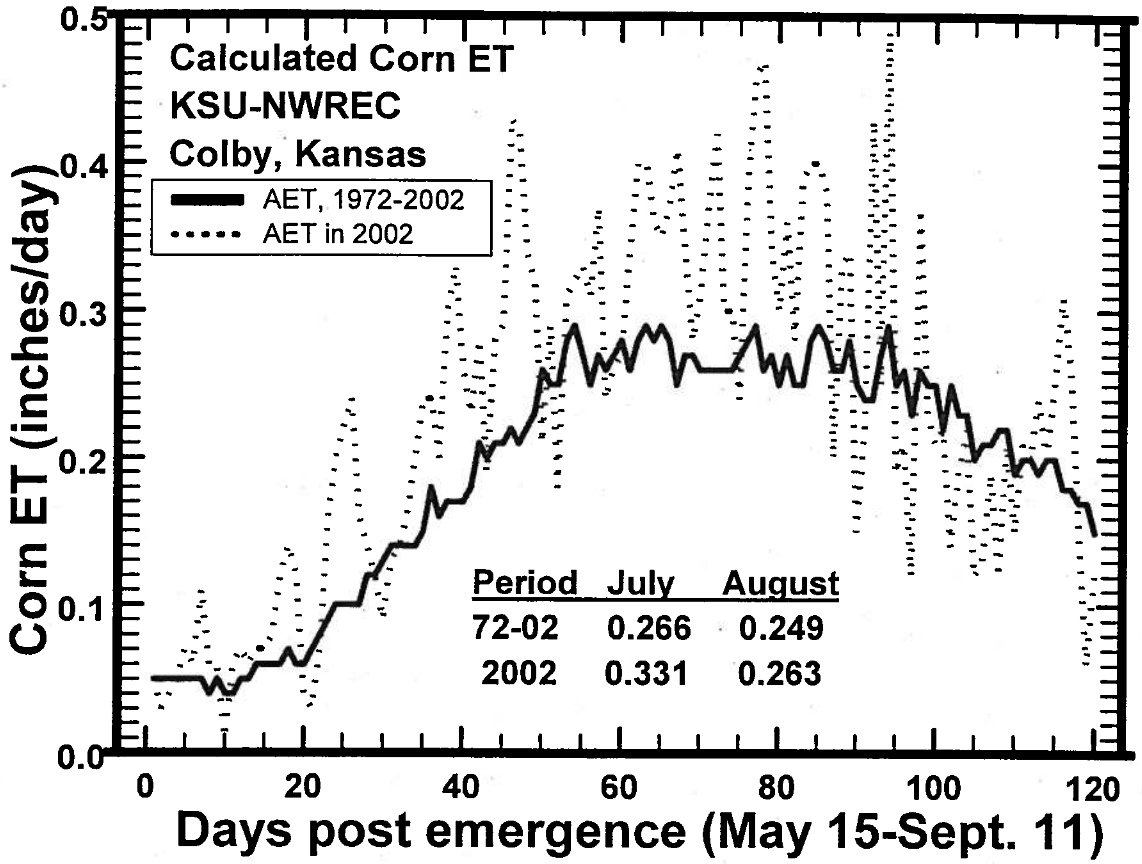

Figure 1. Long term corn evapotranspiration (ET) daily rates and ET rates for 2002 at the KSU Northwest Research-Extension Center, Colby Kansas. ET rates calculated using a modified Penman approach (Lamm et. al., 1987).

DESIGN IRRIGATION CAPACITIES

USDA-NRCS guidelines

The USDA-NRCS National Engineering Handbook (USDA-NRCS, 1997) and through its state supplements for Kansas (USDA-NRCS-KS, 2000, 2002) offer some suggested guidelines for center pivot sprinkler irrigation capacities. A complete description of the calculation procedures used to arrive at these guidelines lies beyond the scope of this paper. However, the minimum gross irrigation capacities in inches/day can briefly be summarized as the net irrigation requirement (NIR) for the July-August (62-day) period for 80 or 50% chance rainfall adjusted for the application efficiency divided by the 62-day period. A summary of this information and its resultant minimum gross irrigation capacities for corn at Colby, Kansas (Thomas county) is shown in Table 1.

Table 1. Summary of USDA-NRCS irrigation capacity guiding parameters and values for corn in Colby, Kansas (Thomas County). Adapted from USDA-NRCS-KS, 2000, 2002.

Parameter	Value	Tab. or Fig.	Source
Seasonal NIR, inches,			
80% chance rainfall	15.4	Table KS4-1	KS Guide, Feb 2000
50% chance rainfall	13.5	Table KS4-2	KS Guide, Feb 2000
Irrigation Zone for Colby, KS.	2	Figure KS4-1	KS Guide, Feb 2000
Irrigation Design Group for Keith silt loam, Colby, KS.	5	I D Group 5	KS Guide, Feb 2000
Monthly distribution of NIR, %			
July % with 80% chance rainfall	40.9%	Table KS4-3	KS Guide, Feb 2000
August % with 80% chance rainfall	32.5%	Table KS4-3	KS Guide, Feb 2000
July % with 50% chance rainfall	43.1%	Table KS4-4	KS Guide, Feb 2000
August% with 50% chance rainfall	33.9%	Table KS4-4	KS Guide, Feb 2000
Minimum center pivot sprinkler gross irrigation capacity, in/day, at stated application efficiency (Ea)			
85% Ea and 80% chance rainfall	0.21	Table KS4-10	KS Guide, Apr 2002
90% Ea and 80% chance rainfall	0.20	Table KS4-11	KS Guide, Apr 2002
85% Ea and 50% chance rainfall	0.20	Table KS4-10a	KS Guide, Apr 2002
90% Ea and 50% chance rainfall	0.19	Table KS4-11a	KS Guide, Apr 2002

The calculation of minimum gross irrigation capacities in this manner violates long standing irrigation design philosophies as is stated in the Irrigation Guide (USDA-NRCS-KS, 2002). However, the rationale is given that center pivot sprinklers in the region typically do not satisfy the peak crop ET without either (1) relying on major withdrawal of root zone soil water rationale for these guidelines or (2) allowing application rates to exceed soil intake rates thus producing excessive runoff. An argument can be made against this rationale in that irrigation runoff might best be handled through sprinkler package selection and the subsequent management of that package rather than through reducing irrigation system capacity.

The USDA-NRCS-KS 2002 guidelines do list the caveat that for dryer-than-average years this design criterion will likely result in plant water stress and reduced yields unless stored soil water reserves can buffer the irrigation system capacity deficiency. However, there might be another point of discussion about the procedure used to calculate the minimum gross irrigation capacity. The calculation procedure uses the July and August monthly distributions of seasonal NIR to determine minimum capacities. The monthly distribution tables also include planning values for the month of May of approximately 1.5 to 4% of NIR. These May planning values might be of good value for preseason planning, but may be detrimental to design of good irrigation management in July and August. Allocation of some monthly distribution to May would result in some reductions of irrigation distributions in June, July and August.

Simulation of corn irrigation schedules for Colby, Kansas

Irrigation schedules (water budgets) were simulated for the 1972-2002 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 for the location (Lamm, 2001) to give the actual corn ET. The irrigation season was limited to the 90 day period between June 5 and September 2 based on results from earlier simulations conducted by Lamm et. al., (1994). 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.

Using this procedure, the mean simulated net irrigation requirement (SNIR) for corn in the 31-year period was 14.6 inches (Table 2.). The maximum SNIR during the 31-year period was 21 inches in 1976, while the minimum was 5 inches in 1992. Monthly distributions of SNIR averaged 15.8, 38.4, 42.8, and 3% for June, July, August and September. However, it might be more appropriate to look at the SNIR in relation to probability. In this sense, SNIR values of 18 and 14.6 inches will not be exceeded in 80 and 50% of the years, respectively (Table 3). These are approximately 17 and 8% higher than the USDA-NRCS-KS guidelines expressed in Table 1, respectively. The minimum gross irrigation capacities (62-day July-August period) generated using the SNIR values are 0.277 and 0.225 inches/day (80% and 50% exceedance levels) for center pivot sprinklers operating at 85% Ea using the simulated monthly distributions (Table 3). These minimum capacities are about 32 and 13% higher than the corresponding values of USDA-NRCS-KS in Table 1.

Table 2. Simulated net irrigation requirements for corn and monthly distributions of irrigation requirements for Colby, Kansas, 1972-2002.

Year	Simulated Net Irrigation Requirement, inches. (SNIR)	June % of SNIR	July % of SNIR	Aug. % of SNIR	Sept. % of SNIR
1972	9	11.1%	44.4%	44.4%	0.0%
1973	15	20.0%	20.0%	53.3%	6.7%
1974	16	12.5%	56.3%	31.3%	0.0%
1975	13	0.0%	46.2%	46.2%	7.7%
1976	21	19.0%	38.1%	38.1%	4.8%
1977	15	20.0%	40.0%	33.3%	6.7%
1978	18	11.1%	44.4%	44.4%	0.0%
1979	8	12.5%	12.5%	62.5%	12.5%
1980	18	16.7%	38.9%	44.4%	0.0%
1981	15	20.0%	40.0%	33.3%	6.7%
1982	16	12.5%	43.8%	43.8%	0.0%
1983	20	10.0%	40.0%	50.0%	0.0%
1984	18	11.1%	55.6%	33.3%	0.0%
1985	15	13.3%	33.3%	46.7%	6.7%
1986	16	12.5%	43.8%	43.8%	0.0%
1987	15	6.7%	40.0%	53.3%	0.0%
1988	18	22.2%	38.9%	38.9%	0.0%
1989	14	7.1%	42.9%	42.9%	7.1%
1990	16	25.0%	37.5%	37.5%	0.0%
1991	15	6.7%	40.0%	53.3%	0.0%
1992	5	20.0%	20.0%	60.0%	0.0%
1993	8	50.0%	12.5%	37.5%	0.0%
1994	16	18.8%	25.0%	50.0%	6.3%
1995	15	6.7%	33.3%	60.0%	0.0%
1996	7	0.0%	42.9%	42.9%	14.3%
1997	13	15.4%	61.5%	15.4%	7.7%
1998	11	36.4%	18.2%	45.5%	0.0%
1999	9	11.1%	55.6%	33.3%	0.0%
2000	19	21.1%	36.8%	42.1%	0.0%
2001	20	20.0%	40.0%	35.0%	5.0%
2002	19	21.1%	47.4%	31.6%	0.0%
Mean	**14.6**	**15.8%**	**38.4%**	**42.8%**	**3.0%**
StDev	**4.1**	**9.8%**	**12.2%**	**10.0%**	**4.2%**
Min	**5.0**	**0.0%**	**12.5%**	**15.4%**	**0.0%**
Max	**21.0**	**50.0%**	**61.5%**	**62.5%**	**14.3%**

Table 3. Simulated net irrigation requirements (SNIR) of corn not exceeded in 80 and 50% of the years 1972-2002, associated monthly distributions and minimum irrigation capacities to meet July-August needs, Colby, KS.

Criteria	***SNIR***	***June SNIR***	***July SNIR***	***Aug. SNIR***	***Sept. SNIR***
SNIR value not exceeded in 80% of years	18 in.	15.8% 2.8 in.	38.4% 6.9 in.	42.8% 7.7 in.	3.0% 0.5 in
July-August capacity	0.236 inches/day				
Min. Gross capacity at 85% Ea	0.277 inches/day				
Min. Gross capacity at 90% Ea	0.262 inches/day				
Criteria	***SNIR***	***June SNIR***	***July SNIR***	***Aug. SNIR***	***Sept. SNIR***
SNIR value not exceeded in 50% of years	14.6 in.	15.8% 2.3 in.	38.4% 5.6 in.	42.8% 6.3 in.	3.0% 0.4 in
July-August capacity	0.191 inches/day				
Min. Gross capacity at 85% Ea	0.225 inches/day				
Min. Gross capacity at 90% Ea	0.213 inches/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 90 day season. *Thus, this procedure is markedly different from the procedure used in the USDA-NRCS-KS 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.

Equivalent irrigation capacities are shown in Table 4.

Table 4. 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 CORN YIELDS AND ECONOMIC RETURNS AS AFFECTED BY IRRIGATION CAPACITY

Model descriptions

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

Irrigated corn yields for the various irrigation capacities were simulated for the same 31 year period (1972-2002) 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 = -184 + (16.85 ET)

with yield expressed in bushels/ acre and ET in inches. Further application of the model reflects weighting factors for specific growth periods. These additional weighting factors are incorporated into the simulation to better estimate the effects of irrigation timing for the various systems and capacities. The weighting factors and their application to the model are discussed in detail by Stone et al. (1995).

Factors associated with the economic model are shown in Table 5.

Table 5. Economic variables and assumptions used in the model.

Revenue streams and field characteristics	
Total field area, acres	160
Center pivot sprinkler area, acres	125
Dryland area, acres	35
Corn harvest price, $/bushel	$2.35
Government payments, $/acre spread over all acres	$27.54
Net returns from dryland area, $/acre	$32.50
Total irrigation system depreciation costs, $/irrigated acre	$93.01
Costs and factors that change with corn yield and irrigation levels	
Corn seed emergence, %	95%
Nitrogen fertilizer, lb/bushel of yield	1.10
Nitrogen fertilizer, $/lb	$0.13
Phosphorus fertilizer, lb/bushel of yield	0.43
Phosphorus fertilizer, $/lb	$0.22
Harvest base charge, $/acre	$18.10
Yield level for extra harvest charge, bu/acre	51
Rate for extra harvest charge, $/bu	$0.135
Hauling charge, $/bu	$0.115
Fuel and oil for pumping, $/inch	$3.34
Irrigation maintenance and repairs, $/inch	$0.33
Interest rate, %	8%
Other variable costs	
Corn seed, $/acre	$34.80
Herbicide, $/acre	$30.48
Insecticide, $/acre	$38.54
Crop consulting, $/acre	$6.50
Crop insurance, $/acre	$10.00
Drying cost, $/acre	$0.00
Miscellaneous costs, $/acre	$10.00
Non-harvest field operations, $/acre	$42.15
Other non-fieldwork labor, $/acre	$5.00
Irrigation labor, $/acre	$5.00
Interest rate, %	8%
1/2 yr. interest for these other variable costs, $/acre	$7.30
Total other variable costs	$189.77

Yield results from simulation

Although corn grain yield is generally linearly related with corn ET from the point of the yield threshold up to the point of maximum yield, the relationship of corn grain yield to irrigation capacity is a polynomial. This difference is because ET and precipitation vary between years and sometimes not all the given irrigation capacity is required to generate the corn yield. In essence, the asymptote of maximum yield in combination with varying ET and precipitation cause the curvilinear relationship. When the simulated results are simulated over a number of years (e.g. 31-year period, 1972-2002) the curve becomes quite smooth (Figure 2.). Using the yield model, the 31 years of irrigation schedules and assuming a 95% application efficiency (Ea), the average maximum yield is approximately 201 bu/acre for the 0.25 inches/day (589 gpm/125 acres or 4.71 gpm/acre) irrigation capacity. The polynomial equations for yield at 95 and 85% application efficiencies are:

$$Y95 = 86 + 33\ Icap + 0.82\ Icap^2 - 0.572\ Icap^3 \qquad (1)$$

$$Y85 = 86 + 30\ Icap + 0.67\ Icap^2 - 0.434\ Icap^3 \qquad (2)$$

where Y95 and Y85 are yields in bu/acre at respective Ea values of 95 and 85% and Icap is the center pivot sprinkler flowrate in gpm/acre.

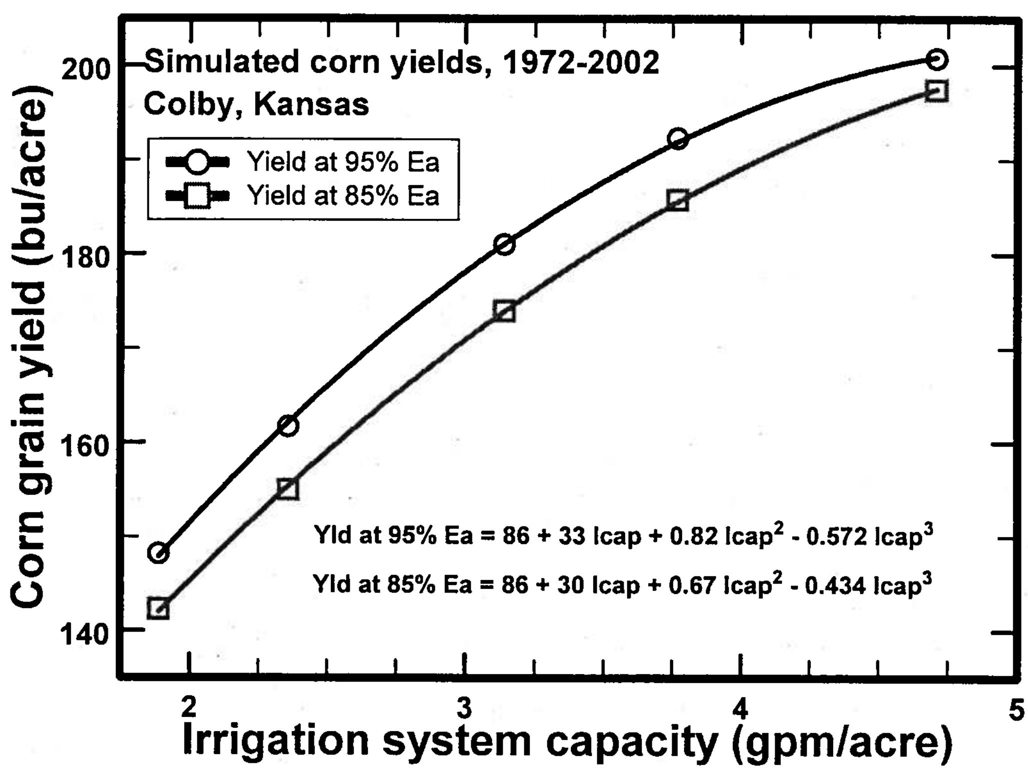

Figure 2. Simulated corn grain yields in relation to irrigation system capacity for the years 1972-2002, Colby, Kansas.

Economic results from simulation

Similarly, these yield results can be coupled with the economic model to generate the simulated net returns to land and management for the same 31 year period (Figure 3).

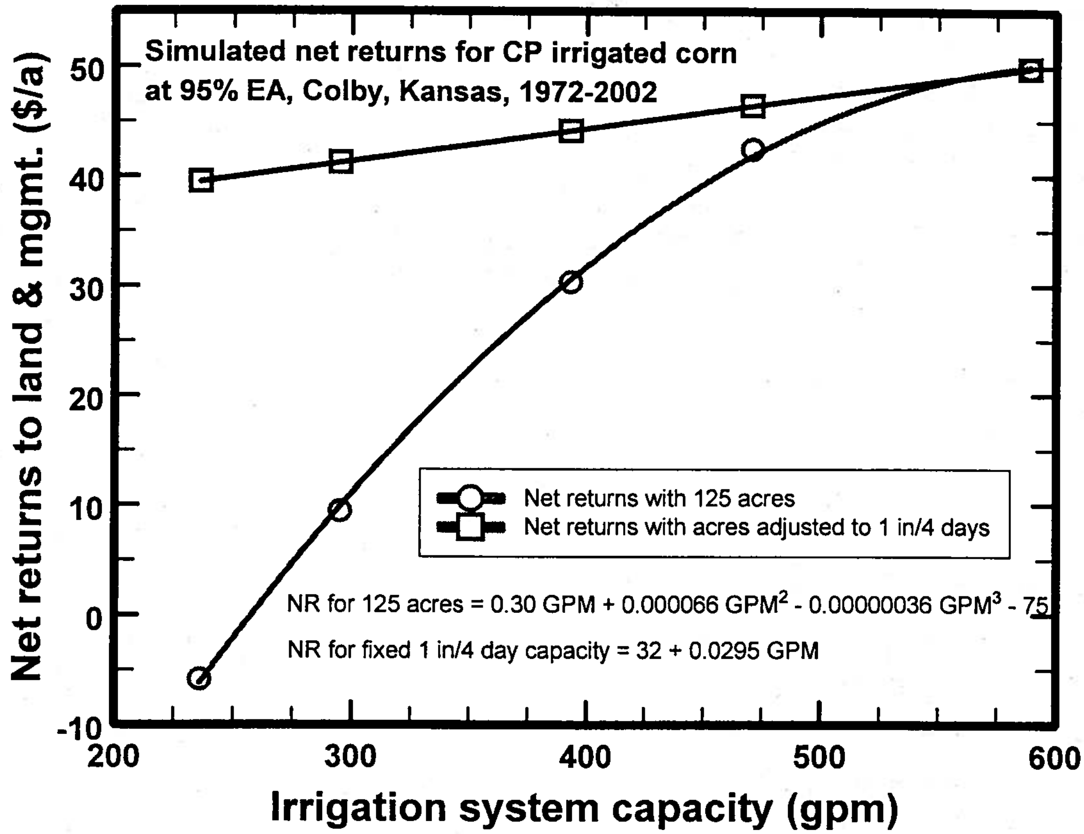

Figure 3. Simulated net returns to land and management for corn production in relation to irrigation system capacity for the years 1972-2002, Colby, Kansas.

Net returns maximized at approximately $50/acre at an irrigation capacity of 589 gpm/125 acres (0.25 inches/day or 4.71 gpm/acre) using the economic assumptions of the model. An alternative scenario where irrigation capacity is fixed at 0.25 inches/day (1 inch/4 days) and center pivot area is allowed to decrease is also shown in Figure 3. Net returns are highest when the gross irrigation capacity is held at the 0.25 inches/day level (1 in/4 days) and irrigated land area is allowed to decrease. It should be noted that fixed irrigation capacity scenarios such as this need to consider what the options are for the area coming out of corn production. In this model, the net returns for dryland production was used as estimated by dryland rent values. It would not be possible to substitute another summer irrigated crop on these acreage reductions because they would be competing for the same irrigation capacity. A winter-irrigated crop could be substituted providing there is sufficient water right available. *It also should be noted that these results are very different from simulations conducted in the mid 1990s where net returns were much higher. In those simulations (data not shown), net returns from the fixed 0.25 inch/day were <u>less</u> than for the full size 125 acre center pivot sprinkler until irrigation system capacity was reduced below 330 gpm/125 acres. <u>This emphasizes how crucial economic assumptions and economic conditions are to the allocation of irrigation and land area.</u>*

The equations for net returns to land and management for center pivot sprinkler irrigated corn are:

$$NR125 = 0.30\ GPM + 0.000066\ GPM^2 - 0.00000036\ GPM^3 - 75 \qquad (3)$$

$$NRFixed = 32 + 0.0295\ GPM \qquad (4)$$

where NR125 and NRFixed are the simulated net returns to land and management in $/acre for irrigated corn for a 125 acre center pivot sprinkler and for alternatively a fixed 0.25 inches/day irrigation capacity.

<u>Yield and economic penalties for insufficient irrigation capacity</u>

The penalties on yield and net returns for insufficient irrigation capacity at a 95% Ea can be calculated for various irrigation capacities (Table 6.)

Table 6. Penalties to corn grain yields and net returns to land and management for center pivot irrigated corn production at 95% Ea when irrigation capacity is below 0.25 inches/day (589 gpm/125 acres). Results are from simulations of irrigation scheduling and yield and economic modeling for the years 1972-2002, Colby, Kansas.

Various equivalent irrigation capacities				***Penalties to***	
Inches/day	GPM/acre	Days to apply 1 inch	GPM/125 acres	Yield, bu/a	Net returns to L & M, $/total 160 acre field
0.250	4.71	4	589	0	$0
0.200	3.77	5	471	8	$1,196
0.167	3.14	6	393	20	$3,122
0.143	2.69	7	337	30	$4,941
0.125	2.36	8	295	39	$6,506
0.111	2.10	9	262	47	$7,823
0.100	1.89	10	236	53	$8,831

Discussion of simulation models

The results of the simulations indicate both yields and net returns to land and management decrease when irrigation capacity was 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 (ET) of a fully irrigated corn crop really has not changed in the last 100 years. Total ET 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. It is possible that it should be further updated to reflect yield advancements. However, it is likely that yield improvements would just shift the curves upward in Figure 2. The effect on Figure 3 would be less clear. It is possible that yield advancements there might indeed shift the profitability of the fixed capacity (0.25 inches/day) line relative to the full 125 acre scenario (curve).

RECENT IRRIGATION CAPACITY STUDIES AT KSU-NWREC

Two different irrigation capacity studies 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., 2003). 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 varied widely. The years 1996-1999 canl 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 4.) 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.

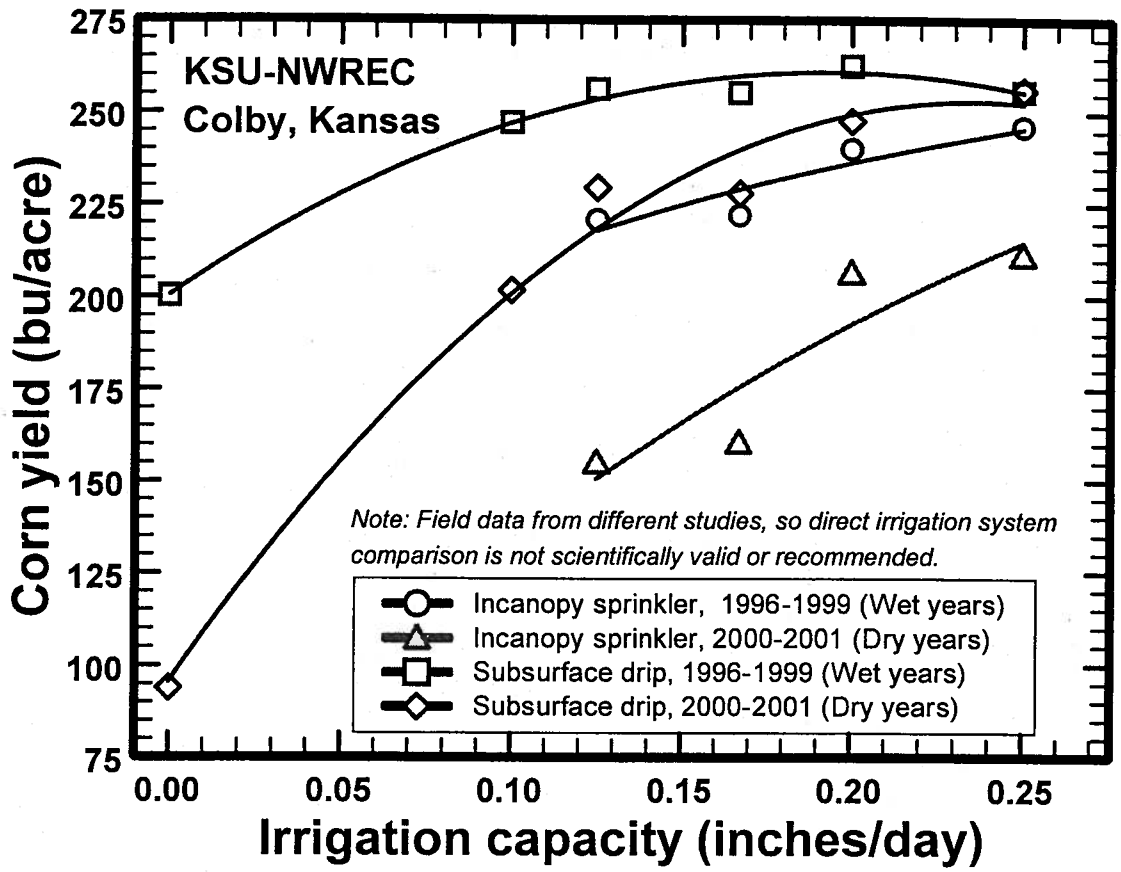

Figure 4. Corn grain yield as affected by irrigation capacity in wet years (1996-1999) and dry years (2000-2001) for two different studies at the KSU Northwest Research-Extension Center, Colby, Kansas.

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 4. 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 corn 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

CONCLUDING STATEMENTS

The question often arises, *"What is the minimum irrigation capacity for irrigated corn?"* 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. Corn can be grown at very low irrigation capacities and there is even dryland corn 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 dryer 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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Estimating Irrigation Pumping Plant Efficiency

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Introduction

Irrigated agriculture in Kansas uses groundwater as the primary water source. Much of the access to this water requires the use of deep wells but even in the more shallow alluvial aquifer systems, energy costs for pumping can be significant. Of course, an increase in energy cost, increase in pumping lift or increase in the total volume pumped causes a direct increase in pumping cost. Pumping costs also increase when changes in pumping conditions and regular wear and tear on pumping plant components result in a loss of pumping plant pumping efficiency.

Pumping Plant Efficiency

Any of the major components of a pumping plant, i.e. the pump, the gear head or drive, or the engine or motor, can be the cause of poor performance. Limited surveys of pumping plants in Kansas indicate the average unit uses about 40 percent more fuel then necessary for the given pumping conditions. In addition, many wells, due to age, initial construction techniques, screen incrustation, and declining water levels, have reduced specific yields. Some of this loss of capacity may be possible to recover with proper well maintenance. High well efficiency should be a concern whenever a replacement well is being considered, as new design and well construction techniques can help obtain good yield with the minimum drawdown during pumping.

Causes of poor pumping plant efficiency

Causes of poor pumping plant efficiency and subsequent excess fuel use include:

1. Poor pump selection.
Pumps are designed to best operate for a particular combination of head and discharge for a given operating speed. If the operating conditions were either not properly matched to a given pump or the conditions changed from the initial conditions, the pump efficiency will be poor.

2. Pumps out of adjustment.
Pumps need to be set to have proper operational clearance. Improper initial adjustment or improper clearance that develops over time due to wear will result in loss of pump efficiency.

3. Worn or broken pumps.
A pump is like any other piece of machinery. It has a useable life span determined by time, use, and operating conditions.

4. Improperly sized engines or motors.
Power plants, especially engines, must be properly selected to operate with the proper loading and operating speed combination to provide good fuel use efficiency.

5. Power plants in need of maintenance or repair.

6. Improperly matched gear heads.
Gear heads (and belt drives) must be properly selected to match the pump and engine speeds and be in good repair.

7. Changes in well performance.
Declining water tables and incrustation build up on well screens effect the yield ability of the well and cause other performance problems , such as cascading water and surging. These conditions may require alteration of the pumping discharge rate.

Estimating pumping plant efficiency

A pumping plant efficiency evaluation can be obtained by hiring a consulting firm of well driller that have the equipment and experience to make the necessary measurements and calculations. As an option, an estimate of the pumping plant efficiency can be made using pumping plant information and on-farm fuel bills. This information can be compared to Nebraska pumping plant performance criteria (NPC). The NPC is a guideline on fuel use requirements for a well designed and properly maintained pumping plant. The estimation of pumping plant efficiency will only be as good as the information used in the estimate.

The comparison can be accomplished by using the K-State Research and Extension Bulletin, L-885, " Evaluating Pumping Plant Efficiency" or using a new computer decision-support software program, called FuelCost. Either method will help determine whether the pumping plant is using more fuel than necessary for the pumping conditions. FuelCost also allows the operator to do some additional fuel related comparisons, such as energy source cost comparison.

Regardless of whether the pumping plant analysis is done using the bulletin or FuelCost, the following information is needed:

1. Acres irrigated,
2. Discharge rate,
3. Total Dynamic Head - estimated using system pressure and pumping lift,
4. Total application amount,
5. Total fuel bill, and
6. Fuel price per unit.

FuelCost can be downloaded from the Mobile Irrigation Lab website at www.oznet.ksu.edu/mil. Other on-line tools are also available at the site. For individuals without web access, check with your local county agent for the bulletin or MIL programs on CD's.

Summary

Irrigation energy costs can be a significant portion of the production costs associated with irrigated agriculture. FuelCost or Extension bulletin L-885 are tools to help irrigators make certain the costs are appropriate for the amount of water pumped for the given field conditions.

Acknowledgment

The Mobile Irrigation Lab is supported in part by the Kansas Water Plan Fund administered by the Kansas Water Office, the Kansas Corn Commission and USDA Project 00-34296-9154.

THE OGALLALA AQUIFER IN NORTHWEST KANSAS – GROUNDWATER AVAILABILITY & USE

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ABSTRACT

A study of the groundwater flow system in the High Plains aquifer in northwest Kansas and small portions of eastern Colorado and southern Nebraska is ongoing as part of a Ph.D. dissertation research program. The research has compiled data from various sources into a consistent GIS geodatabase, collected detailed data in two study areas, performed statistical analyses to define key variables controlling water levels and water level declines, and developed a groundwater flow model for the area. Historical water use estimates have been made based on observed water use, well permits, and precipitation. The key variable for explaining nonpumping water levels is ground surface elevation. The statistically significant variables for explaining water level declines are ground surface elevation, water use, recharge, and saturated thickness. From theoretical calculations and observed data it was determined that pumping rates will start to decline when the saturated thickness becomes less than 40 to 70 feet depending on the hydraulic conductivity at a given well location.

INTRODUCTION

A detailed study of the groundwater conditions in the High Plains aquifer in northwestern Kansas including all of Groundwater Management District (GMD) 4, eastern Colorado, and southern Nebraska (Figure 1) is ongoing. The overall objectives of this study are:

- Identify the statistically significant variables that affect the nonpumping groundwater levels and level declines. This objective is addressed in this paper.
- Develop numerical and statistical predictive models that can be used to predict irrigation well performance and future groundwater level declines. One potential use of these models would be to assess the effects that various agricultural practices may have on these declines. The irrigation well performance is addressed in this paper.

- Assess the effect that input data errors have on the ability to predict water level declines and irrigation well performance. This objective is not discussed in this paper.

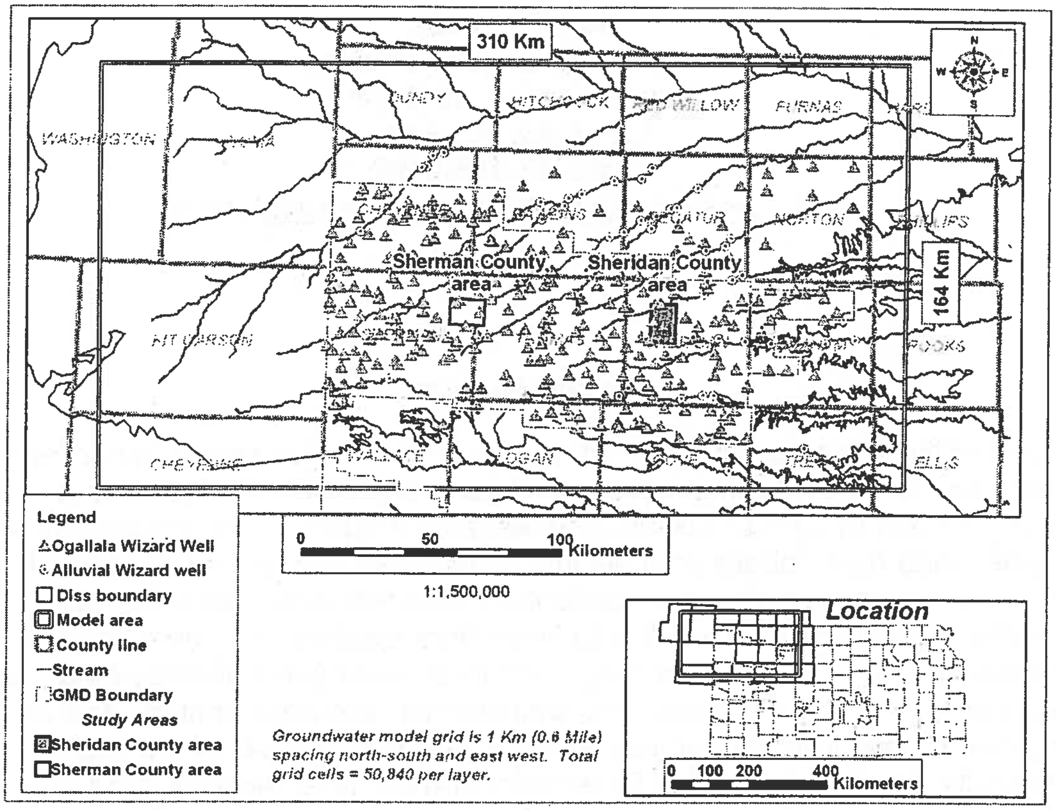


Figure 1. Location of overall study area and Sherman and Sheridan County detailed study areas.

The activities presented in this progress report on the ongoing research are:

- The data compilation program for the entire study area to acquire the publicly available data that exists for the area and put these data into a consistent geodatabase. These data were evaluated for overall consistency using a groundwater flow model of the area.
- Results from the data collection program to collect detailed continuous and monthly water levels and well pumping data in Sherman and Sheridan Counties.
- Estimation of historical groundwater use
- Statistical analysis of water levels and water level declines
- Calculation and observation of drawdown in irrigation wells during irrigation season

DATA COMPILATION

The objective of the data compilation program is to collect publicly available data generated by various organizations and compile it into a consistent spatial and temporal format so it can be used readily throughout the large study area. The data and sources included in this effort include:

- Temporal data
  - Water levels from the Kansas Geological Survey (KGS, http://www.kgs.ku.edu/Magellan/WaterLevels/index.html) and U.S. Geological Survey (USGS) (http://webserver.cr.usgs.gov/nawqa/hpgw/GIS.html)
  - Water level decline data from the USGS (http://webserver.cr.usgs.gov/nawqa/hpgw/GIS.html)
  - Stream flow from the USGS (http://ks.waterdata.usgs.gov/nwis)
  - Groundwater use for Kansas from WIMAS database (individual wells by year, http://mapster.kgs.ukans.edu/dasc/catalog/coredata.html)
  - Precipitation data from National Oceanic and Atmospheric Administration (NOAA, http://www.ncdc.noaa.gov/oa/climate/stationlocator.html)
  - Crop production data from National Agricultural Statistical Services (NASS, http://www.nass.usda.gov:81/ipedb/)
- Groundwater appropriation data for Colorado from Colorado Division of Water Resources
- Geology, hydrogeology, and recharge data from USGS (http://webserver.cr.usgs.gov/nawqa/hpgw/GIS.html and http://water.usgs.gov/lookup/getgislist) and KGS (http://mapster.kgs.ukans.edu/dasc/catalog/coredata.html)

All of the spatial data were compiled into a geographical information system (GIS) geodatabase. These data are accessed processed using ArcGIS™ version 8.2. All of the non-spatial data were organized into Excel™ spreadsheets by data type and then exported into the geodatabase as tables. To the extent possible, the tabular data were joined to the appropriate spatial data locations in the GIS.

To assess the usability and consistency of the data compiled from these, the hydrogeologic data that may affect water level declines were input into a groundwater flow model based using the model code MODFLOW (Harbaugh and McDonald, 1996; McDonald and Harbaugh, 1988). The water levels simulated with this model were compared to the predevelopment water levels derived by the USGS (Cederstrand and Becker, 1999). The results of this analysis are presented on Figure 2. As shown, the simulated water levels match reasonably close to the observed data. A sensitivity analysis was performed on the published data values and the published values were found to give the most reasonable model results. The sensitivity analysis was performed by varying the input parameter and comparing the model result with the model result using published values. For example, recharge estimates were increased two higher than the published data and the simulated water levels were noticeably higher than the observed water levels, the mean residual of observed-computed were higher negative values and the statistical errors were greater (Figure 3). From this type of sensitivity analysis, it is concluded that there are no large-area discrepancies in the published data.

DETAILED DATA COLLECTION

To collect detailed data over relatively small areas for purposes of defining hydrogeologic controls and water level changes over time, two detailed study areas were setup in Sherman and Sheridan counties in Kansas (Figure 1). In each of these areas, a monthly water level and pumping rate monitoring program was implemented and one well in each area was instrumented with a recording water level transducer that measured and stored water levels at a one-hour interval. The geologic and hydrogeologic data for each area were developed from existing well logs and pumping tests.

ESTIMATED GROUNDWATER USE OVER TIME

In the study area, there are approximately 7000 pumping wells (Figure 4). Water use is potentially a very important variable in the assessment of the groundwater in the study area but for most of the period of pumping, these data were not collected and thus two methods were developed to estimate historical water use. One method was developed for Kansas, where groundwater use data have been collected since 1990 and well appropriation data are available and a different method was developed for Colorado where use data over time are not available but well appropriation data are available.

Usability of groundwater use data for Kansas

Since 1990, Kansas has required the reporting of annual water use for most permitted wells to the Kansas Department of Agriculture, Division of Water Resources. For the Kansas portion of the study area, records exist for approximately 3500 wells and these data have been compiled into a database by individual well permit. Although the number of metered wells has steadily increased since 1990 (Figure 5), less than 20% of the wells are metered. Therefore one question that was addressed in this analysis is the validity of the use data for the unmetered wells. This is important because this decade of use data serves as the foundation for several subsequent analyses.

To check for an overall bias in the use data, a simple comparison of water use per acre irrigated was conducted for the metered and unmetered wells. The results are presented on Figure 5 and show that on a per-acre-irrigated basis, there is no overall bias for the unmetered wells.

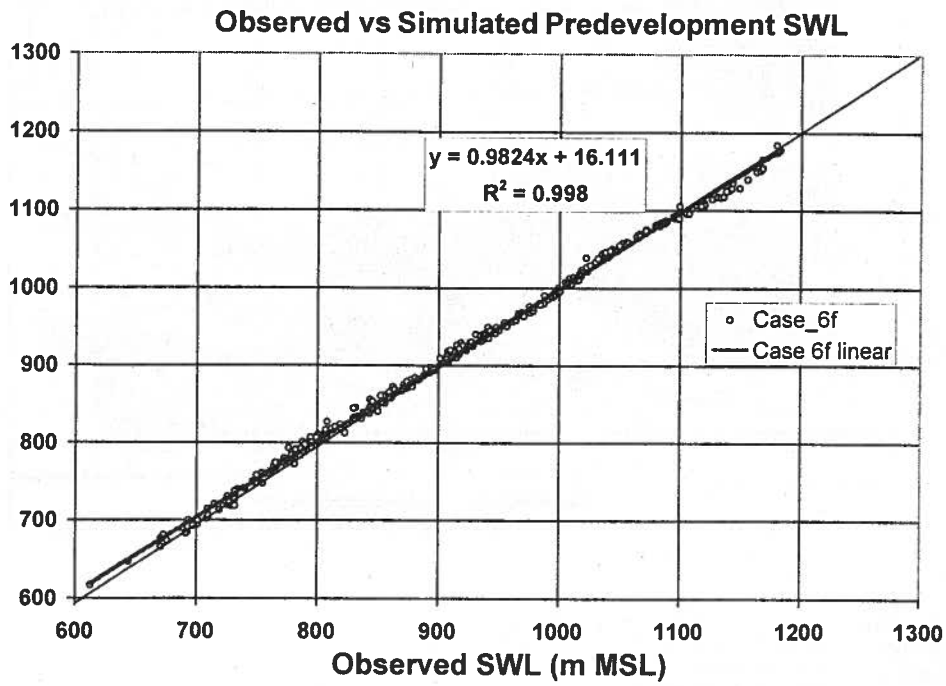


Figure 2. Simulated vs observed groundwater level elevations (in meters) used as a data consistency check of published data. Ideal fit would have a regression equation of y = 1.00 x + 0.00 and would plot on the diagonal line.

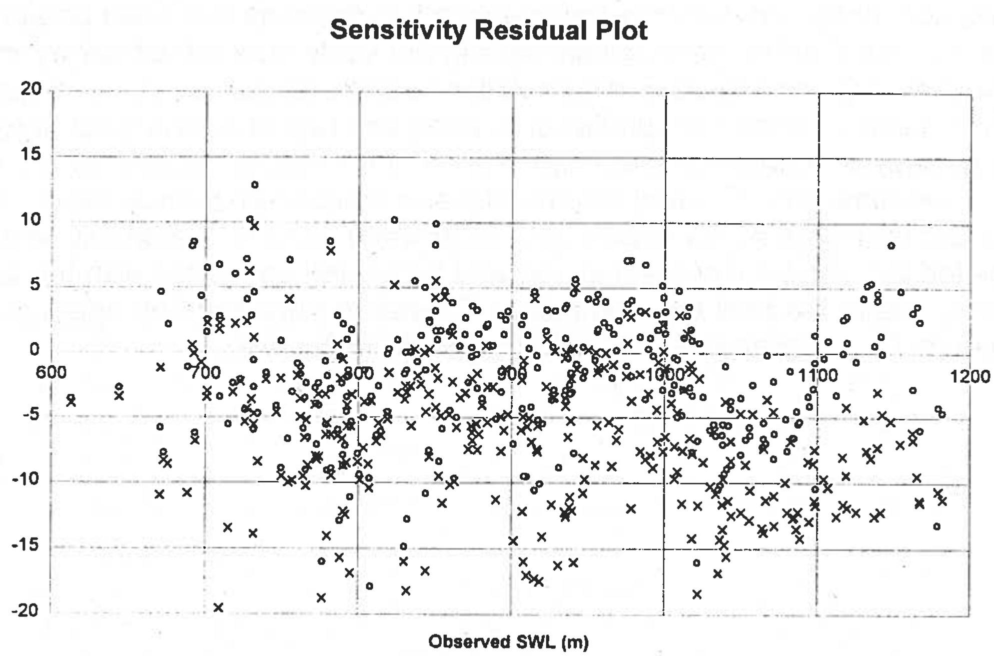


Figure 3. Residual plots from sensitivity analysis. The R 2X case had the recharge rate doubles across the model area and the sum of squared residuals increased by almost three times and the mean residual increased by over four times.

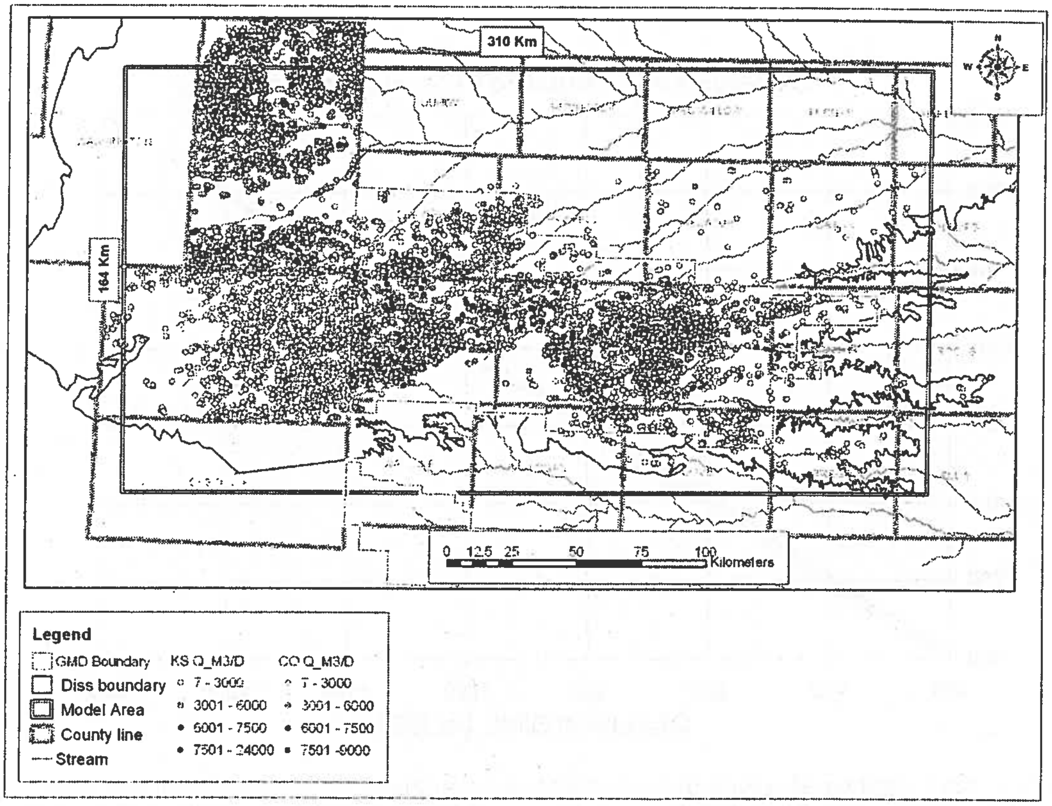


Figure 4. Large capacity wells (> 100 gpm). Most wells on this figure are used for irrigation.

The reason for this consistency between the two datasets can likely be attributed to the fact that most of the irrigation wells in the study area are power by internal combustion engines that have a cumulative hour meter as part of the engine instrumentation. Since the number of nozzles and rate of nozzle discharge (gpm/nozzle) are known for each center pivot, it is relatively simple for the water user to calculate a reasonable volume of water used on an annual basis. As presented on Figure 6, the annual volume of water used is reasonably well correlated with the total hours pumped and is not well correlated with the total pumping rate or the total acres irrigated. Therefore relying on the hours pumped appears to be a reasonable way to approximate water use.

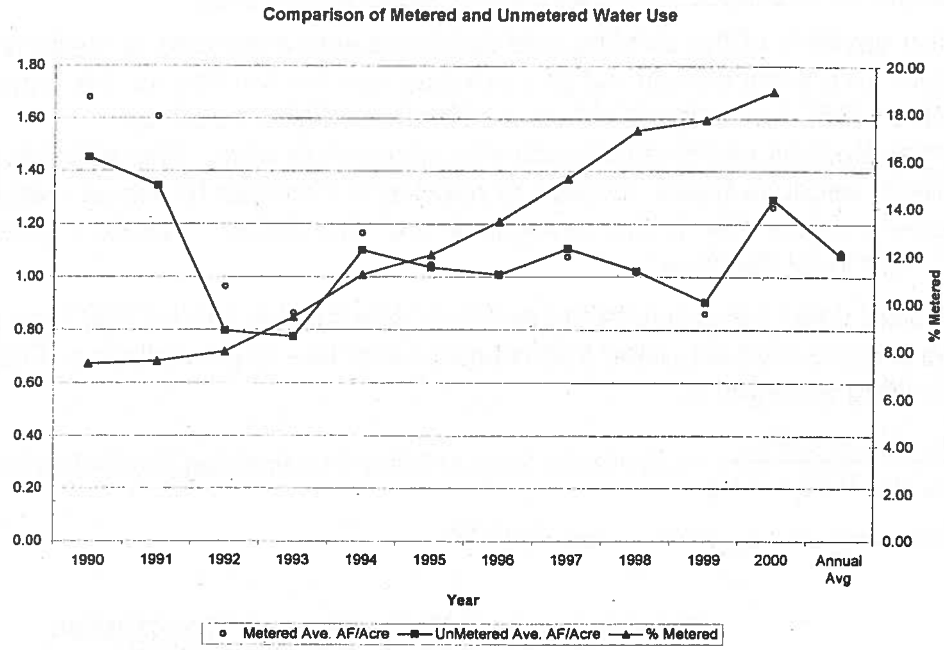


Figure 5. Comparison of metered and unmetered data in terms of water used per acre irrigated. This was a check of the validity of the unmetered use data.

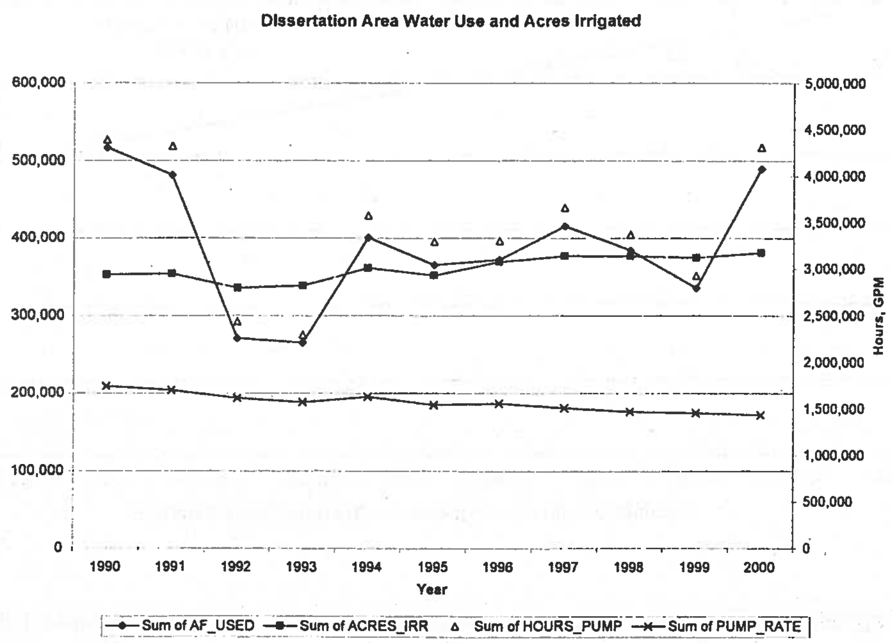


Figure 6. Relationship between volume of groundwater used, hours pumped, pumping rate, and acres irrigated for the period from 1990–2000. *Note that in this analysis and subsequent analyses where totals for a given parameter are presented, the data from the individual wells have been totaled and the respective values are presented on the various graphs in this report. For example, on the above graph, the hours pumped was derived by totaling the hours pumped for all wells for each year. Total values for acres irrigated, acre-feet used, and gallons per minute were derived in the same manner.*

Estimates of historical groundwater use for Kansas

Once the usability of the existing use database was assessed, a method was developed to predict the annual groundwater use for Kansas for the time period from 1965–1989 for each individual well in the WIMAS database (http://mapster.kgs.ukans.edu/dasc/catalog/coredata.html). This effort was undertaken because these values are needed to simulate historical water level declines—a critical step in the development of simulation methods to predict future water level declines.

The method used the precipitation and use data for the 1990–2000 time period to develop a regression equation that relates water use to precipitation (Figure 7). The resulting equation is:

$$\frac{\textit{Annual use (AF)}}{\textit{Average use } 1990-2000} = \textit{Deviation from Average Precipitation (in)} \times -0.0451 + 1.0581$$

$$R^2 = 0.40, \quad \textit{regression prob-value} = 0.0376$$

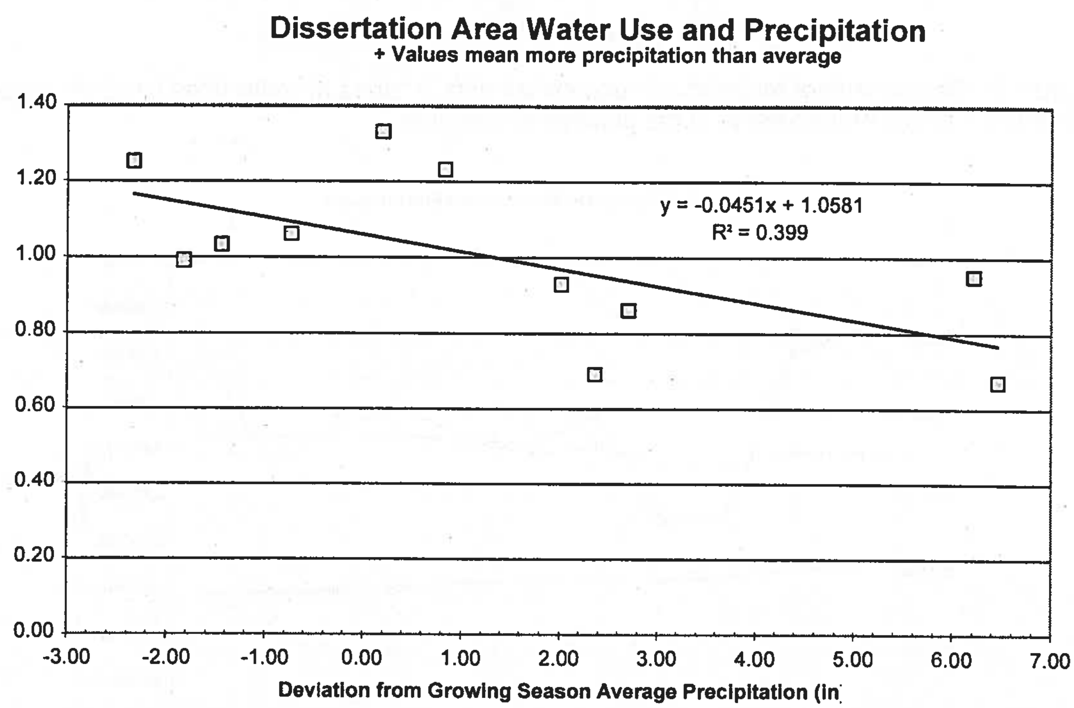


Figure 7. Regression of irrigation water use and precipitation for northwest Kansas 1990–2000. The statistical prob-value of the regression is 0.0376 and so the regression statistically significant.

The water use ratio and precipitation deviation values were used in the equation because they made the derived equation easier to apply to the historical dataset being evaluated. The same regression could be developed using the annual precipitation/water use data, with different equation coefficients.

This regression equation was applied to the individual wells for the time period of 1955–1989 by first assuming that a given well became operational one year after the given permit was granted. The second assumption was that the average annual groundwater usage for the 1955–1989 period was 20% higher than the average observed usage for 1990–2000. This higher usage rate was assumed because the 1990–2000 period had slightly higher annual precipitation than the annual average (19.97 vs 21.56 inches) and water use became more efficient when low-pressure center pivot irrigation methods replaced high-pressure pivot and flood irrigation methods in the late 1980's and early 1990's.

The results for the entire Kansas portion of the study area are presented on Figure 8 along with the harvested irrigated acreage data from 1970–2001 (irrigation acreage data is not available for prior years). As shown the average calculated water use is about 1.5 acre-feet of irrigation water per acre irrigated. For the study area, this is consistent with prior estimates for water use of between one and two acre-foot per acre irrigated depending on the crop type (Heimes and Luckey, 1982, 1983). As presented, the estimated water use corresponds reasonably well with the irrigated acreage values with more use variability in the decade where use data are available. The lower use and higher variability in the 1990–2000 time period compared to the acres irrigated can be attributed to more efficient low-pressure nozzle irrigation practices and the smoothing effect that the regression equation has on the calculated historical use estimates.

Estimation of historical groundwater use for Colorado

The estimation of historical water use for the Colorado portion of the study area was more problematic because annual use reporting is not conducted and water levels are not routinely measured. Therefore, to estimate Colorado water use, the appropriation data were compiled with each well assumed to start pumping the year following the granting of the permit. The average annual use rate was set at 50% of the volume of water appropriated on the permit. If just a flow rate was listed for the appropriation instead of an annual total volume, it was assumed that the well was pumped for 90 days per year at a rate that was 50% of the appropriated rate. The precipitation–use regression equation from Kansas was then applied to the individual well data to adjust for annual differences in precipitation.

STATISTICAL ANALYSIS OF WATER LEVELS AND WATER LEVEL CHANGES

The data from the preceding tasks were analyzed using standard statistical methods for regression and multivariate regression (Rogerson, 2001). The purpose of these regression evaluations was to statistically determine the major controlling factors on water levels and water level changes. In the study area, there are areas of water level rises as well as areas of water level declines (Figure 9) and the statistical analysis of water level change had to accommodate these differences.

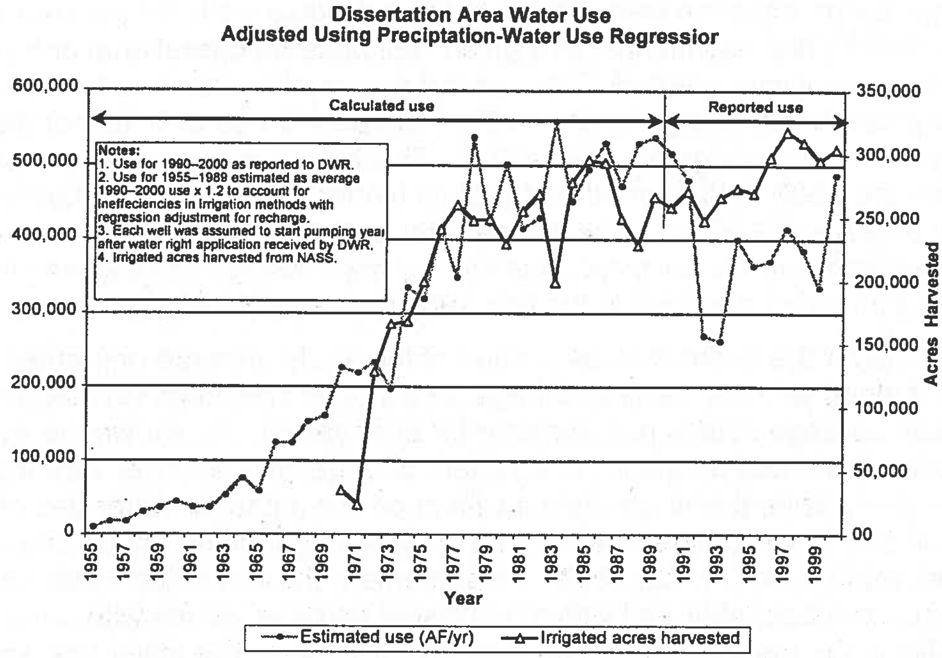


Figure 8. Calculated total water use in northwestern Kansas for 1955–1989 and observed water use from 1990–2000 and irrigated crop acreage as reported to NASS. The total water use values were derived from individual well estimates or observations.

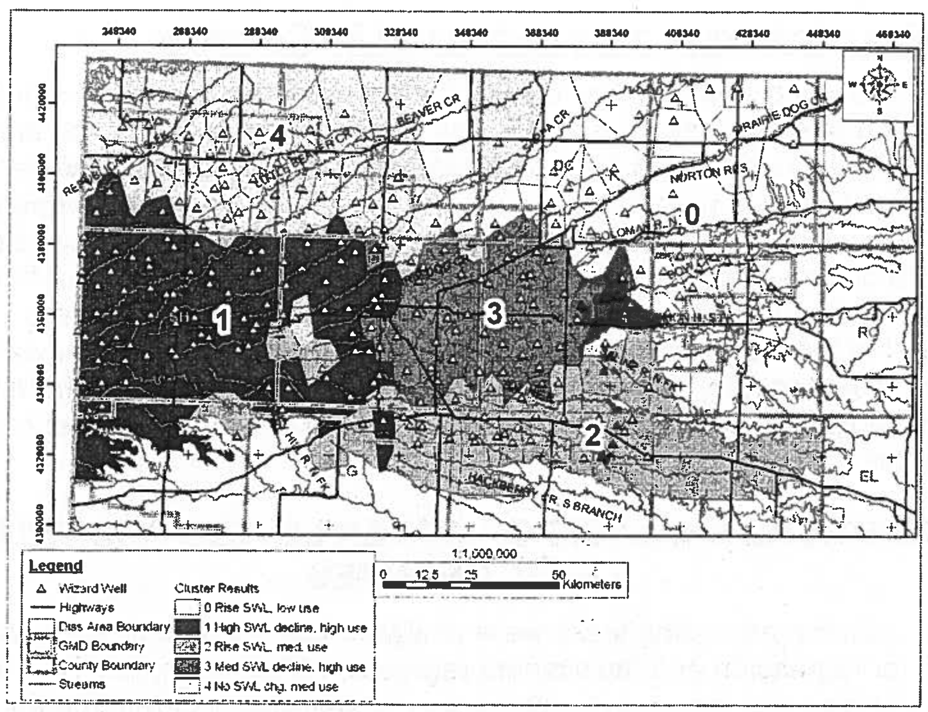


Figure 9. Cluster analysis results defining areas of water level declines and rises over the period from 1990–2001. Cluster analysis was performed using Loiczview clustering at (http://www.palantir.swarthmore.edu/loicz/) with GIS post-processing to create Tessellation polygons around each Wizard well used.

Statistical determination of factors related to nonpumping water levels

Based on simple regression of the nonpumping water levels and various independent variables, it was determined that the nonpumping water levels were closely related to the ground surface elevation at the individual wells measured (Figures 10 and 11). Based on the regressions for two separate dates shown on Figures 10 and 11, approximately 99% of the variability observed in the nonpumping water levels can be explained by topographic ground surface elevation. Hydrogeologically, this means that the High Plains aquifer flow system in northwest Kansas is dominated by topography with other variables such as hydraulic conductivity, recharge, and saturated thickness explaining less than 1% of the variability under nonpumping conditions. This is consistent with the theoretical work of (Toth, 1962; 1963; 1970) and numerical simulations of (Freeze and Witherspoon, 1966; 1967; 1968).

Statistical determination of factors related to water level declines

The factors controlling water level declines are somewhat more complicated than the nonpumping water level factors. As presented in the correlation matrix of the various variables (Figure 12), the rate of water level decline is related to several variables. Therefore, multivariate regression was conducted using the water level decline rate as the dependent variable and the other variables as the independent variables even though several of these variables are obviously correlated with each other.

Because of these correlations, the step-wise multivariate technique (Rogerson, 2001) was used to develop the regression so that only the most statistically significant variables were selected for the final regression. This technique accommodates the correlations (multicollinearity) between independent variables at each step in the calculation process. Therefore, if two correlated variables exist in a dataset, only one of these variables will enter into the final regression equation. In the correlation matrix (Figure 12), ground surface and aquifer bottom elevation are highly correlated. In step-wise regression, only one of these variables can enter into the final equation. This is because the amount of variability that the second variable can explain after the first is entered into the equation is small compared to the other variables.

The resulting multivariate regression equation (Figure 13) in metric units is:

$$\textit{Rate of water level decline} = 0.423 - 0.00041(\textit{GS\_elev}) + 720(\textit{Recharge\_rate}) - 0.0124(\textit{Water use}) - 0.0015(\textit{staturated thickness})$$

$$R^2 = 0.57, \quad \textit{regression prob-value} < \textit{0.0001}$$

The regression equation in English units is:

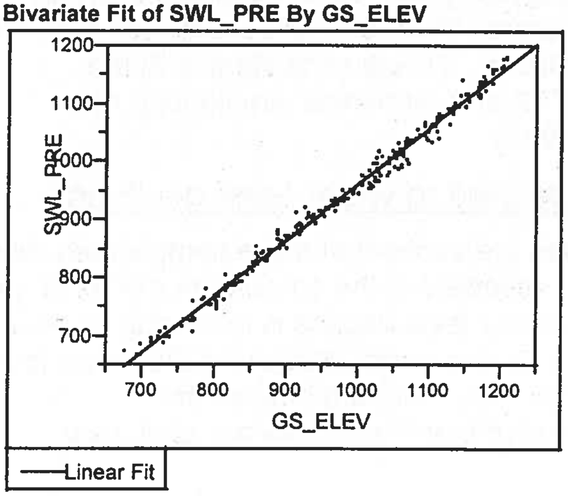
$$\textit{Rate of water level decline} = 1.42 - 0.00041(\textit{GS\_elev}) + 0.164(\textit{Recharge\_rate}) - 0.0050(\textit{Water use}) - 0.0015(\textit{staturated thickness})$$

$$R^2 = 0.57, \quad \textit{regression prob-value} < \textit{0.0001}$$

where:

- Rate of water level decline in meters/year or feet/year (1 meter = 3.28 feet)
- Ground surface elevation and saturated thickness in meters or feet
- Recharge rate in meters/day or inches/year
- Water use in hectare-meters/year/Km^2 or acre-feet/year/Km^2 (1 acre-foot = 0.12334 hectare-meter)

Bivariate Fit of SWL_PRE By GS_ELEV



Linear Fit

SWL_PRE = -5.876108 + 0.9691084 GS_ELEV

Summary of Fit

RSquare	0.991416
RSquare Adj	0.991384
Root Mean Square Error	11.93636
Mean of Response	931.0479
Observations (or Sum Wgts)	268

Analysis of Variance

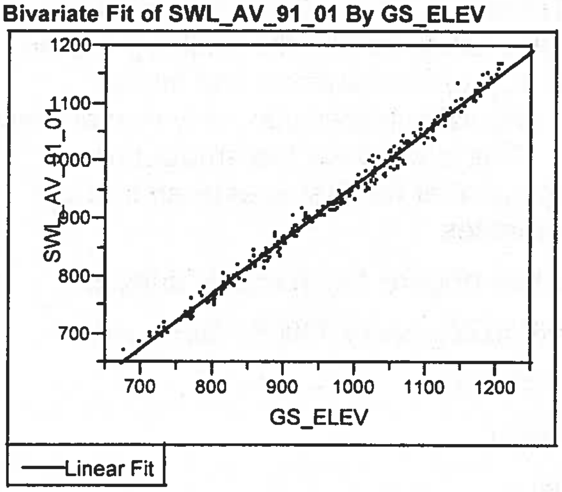
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	4377117.8	4377118	30721.64
Error	266	37898.8	142	Prob > F
C. Total	267	4415016.6		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-5.876108	5.394923	-1.09	0.2771
GS_ELEV	0.9691084	0.005529	175.28	<.0001

Figure 10. Simple regression of predevelopment water level elevations and ground surface elevation.

Bivariate Fit of SWL_AV_91_01 By GS_ELEV



Linear Fit

SWL_AV_91_01 = 17.276484 + 0.9405464 GS_ELEV

Summary of Fit

RSquare	0.99114
RSquare Adj	0.991107
Root Mean Square Error	11.77086
Mean of Response	926.587
Observations (or Sum Wgts)	268

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	4122910.8	4122911	29756.88
Error	266	36855.2	139	Prob > F
C. Total	267	4159765.9		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	17.276484	5.320122	3.25	0.0013
GS_ELEV	0.9405464	0.005452	172.50	<.0001

Figure 11. Simple regression of average nonpumping water level from 1991–2001 and ground surface elevation.

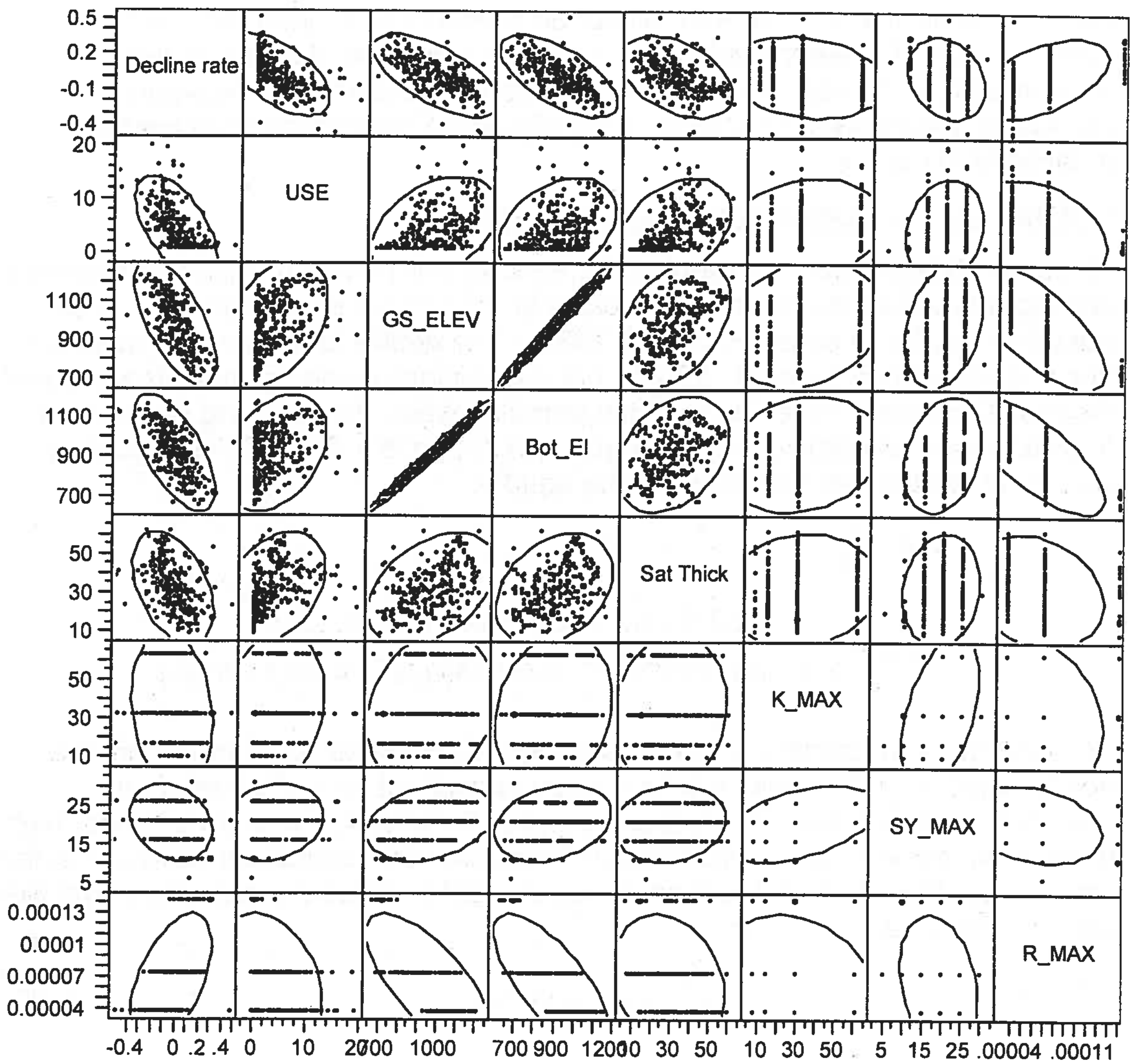


Figure 12. Correlation matrix of selected variables. Decline rate (water level decline rate) is in m/yr, USE (groundwater use) is in hectare meters/ Km^2/yr, GS_Elev (ground elevation), Bot_El (base of aquifer elevation), Sat Thick (saturated thickness) are all in m, K_MAX (hydraulic conductivity) is in m/d, SY_MAX (specific yield) is a percentage, and R_MAX (recharge) is in m/d.

DETERMINATION OF IRRIGATION WELL DRAWDOWNS DURING PUMPING

While the previous analyses determined factors that can affect the nonpumping water levels, water level declines, and associate affected area, one critical question is when will individual wells be affected by water level declines? In other words, how much saturated thickness is required before the yield will start to decline?

Once the saturated thickness in an area of the High Plains aquifer declines to a certain minimum thickness, the well yield will start to decrease because the available drawdown (the difference between the nonpumping water level and the pumping water level) in the well will not be sufficient to support the desired pumping rate. To determine the required thickness, both theoretical and observed irrigation well drawdown values were assessed. The theoretical drawdown values were compared to the observed drawdowns from the two detailed study areas.

Calculated drawdown for irrigation wells

The theoretical drawdowns required for various well pumping rates and hydraulic conductivity values were calculated using standard well interference methods based on the Theis equation (Theis, 1935). The details of the method used are documented in (Hecox et al., 2002). For calculations involving multiple wells and the resulting interference between the pumping wells, the following polynomial approximation (Abramowitz and Stegun, 1972) , eq. 5.1.53) of Theis equation was used to calculate drawdown in the *aquifer*:

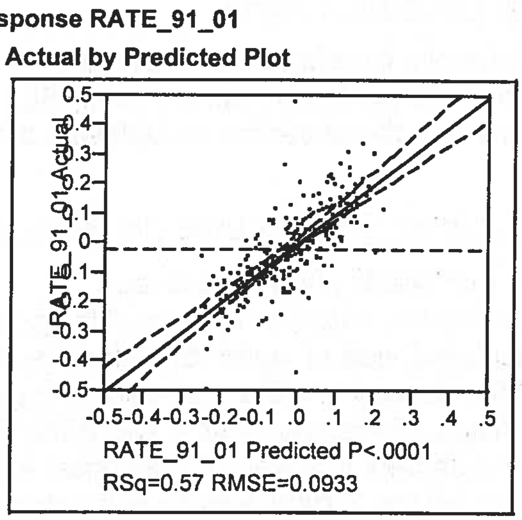
$$u = \left(\frac{r^2 S}{4Tt}\right)$$

$$s_{aquifer} = \frac{Q}{4\pi T}\begin{bmatrix} -0.5772 - \ln u + 0.99999u - 0.24991055u^2 \\ +0.05519968u^3 - 0.00976004u^4 + 0.00107857u^5 \end{bmatrix}$$

To account for the additional drawdown required for water to migrate from the aquifer into the well screen, it is necessary to account for well losses in the theoretical calculations. This is because even for a new, properly designed, high production rate well, the well efficiency (drawdown in the aquifer/drawdown in the well) is usually only 70–80 percent (Driscoll, 1986). Thus the drawdown in a well was calculated as:

$$s_{well} = s_{aquifer} + 0.5(s_{aquifer}).$$

The results for the theoretical drawdown calculations for a range of pumping rates for wells on 1/4 mile spacing are presented on Figure 14 for various values of hydraulic conductivity. Using the hydraulic conductivity histogram (Figure 15) for the hydraulic conductivity values from pumping tests conducted in the GMD 4 area, it can be concluded that the majority of the irrigation wells in northwest Kansas may start to be impacted when the nonpumping saturated thickness declines to between 40 and 60 feet for a 400 gpm well and between 60 and 120 feet for a 1000 gpm well.



Summary of Fit

RSquare	0.57364
RSquare Adj	0.567155
Root Mean Square Error	0.093309
Mean of Response	-0.01792
Observations (or Sum Wgts)	268

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	4	3.0808414	0.770210	88.4623
Error	263	2.2898493	0.008707	Prob > F
C. Total	267	5.3706907		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.4232536	0.075922	5.57	<.0001
GS_ELEV	-0.000407	0.000067	-6.05	<.0001
R_MAX	719.99962	316.5396	2.27	0.0237
HM_Sq_Km_yr	-0.0124	0.001631	-7.60	<.0001
B_91_01	-0.001491	0.000553	-2.70	0.0075

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
GS_ELEV	1	1	0.31897550	36.6358	<.0001
R_MAX	1	1	0.04504634	5.1738	0.0237
HM_Sq_Km_yr	1	1	0.50336005	57.8133	<.0001
B_91_01	1	1	0.06323751	7.2631	0.0075

Figure 13. Multivariate regression with water level decline as dependent variable and ground surface elevation (GS_ELEV), recharge (R_MAX), water use (HM_Sq_Km_yr), and saturated thickness (B_91_01) as independent variables.

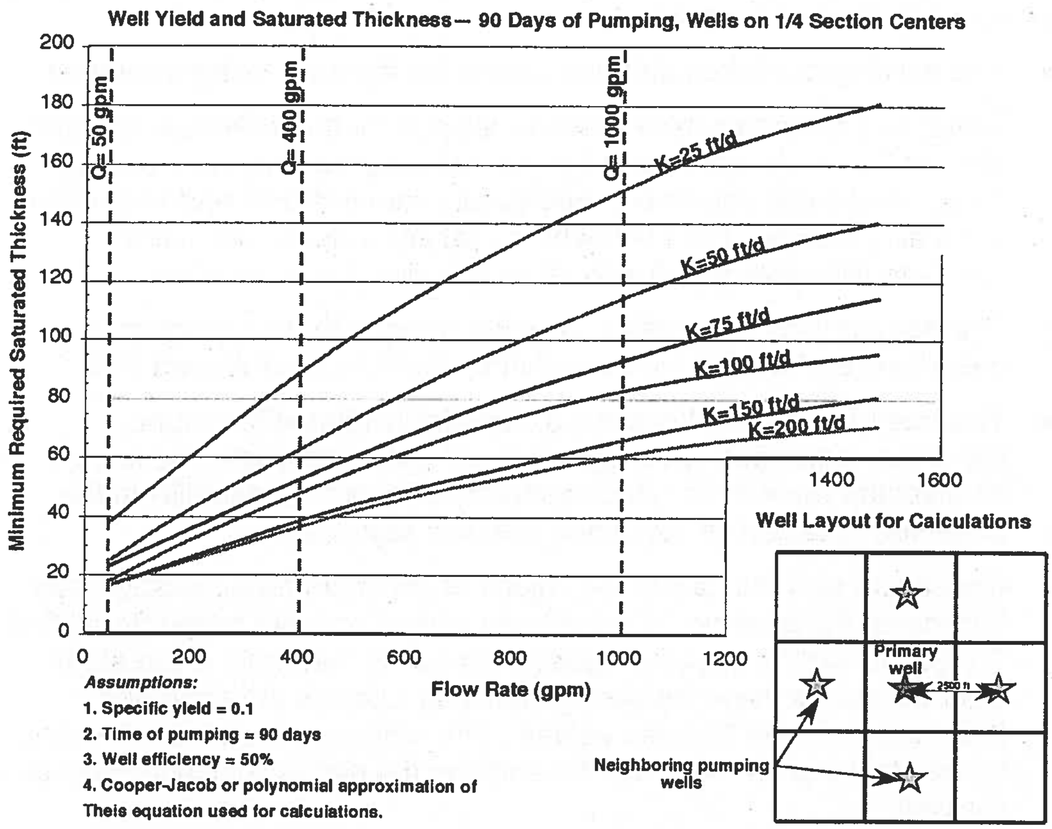


Figure 14. Curves of required saturated thickness as a function of pumping rate and aquifer hydraulic conductivity. See section 3.1 of (Hecox et al., 2002) for detailed discussion.

Observed drawdown in high capacity irrigation wells

The observed drawdowns in the wells in the two detailed study areas are presented on Figure 16. Most of the wells were pumping approximately 500 gpm with a range from 240 to 1050 gpm. As shown, the observed drawdowns are between 25 and 70 feet.

Calculated areas of water level drawdown during pumping season

Observed water level data does not exist that would allow for a direct determination of the area of drawdown during the irrigation season. Using the calibrated model presented above, a calculated area of water level decline after 21 years of pumping has been prepared for Kansas and is presented on Figure 17. This simulation includes all of the individual irrigation wells in the WIMAS database for the period 1980–2000. As presented, the area of drawdown at the end of the irrigation season is primarily around the irrigation wells and extends from 2 to 8 kilometers (one to five miles) out from areas with closely spaced irrigation wells. Work is ongoing to refine this area of drawdown

CONCLUSIONS AND ONGOING EVALUATIONS

The analyses and findings in this report are being incorporated into the overall understanding of how the study-area portion of the High Plains aquifer functions and how it responds to water use and changing hydraulic conditions. To date the major conclusions and analyses are:

- The existing published data are usable for the area being evaluated.
- Water use estimates have been developed for the individual irrigation wells in Colorado and Kansas using available use and precipitation data. These use values are calculated estimates only and should be used accordingly. The overall historical use values calculated compare reasonably well with other historical use estimates.
- The nonpumping water levels are correlated with the topographic elevations at the wells with correlation coefficients of around 0.99.
- The rate of water level decline is statistically related to ground elevation, water use, recharge rate, and saturated thickness using multivariate regression. Approximately 57% of the variability in the observed data can be explained with this regression.
- Consistent with the calculated values of minimum required saturated thickness, the observed drawdowns in irrigation wells range from 25 to 70 feet during the irrigation season indicating that wells in the study area will start to have reduced production rates as the saturated thickness declines to these values. The required saturated thickness to maintain a given flow rate depends on the hydraulic conductivity at the well.

- The area of water level decline is calculated to extend one to five miles away for concentrated areas of irrigation wells.

The dissertation study is proceeding in the following areas:

- The numerical MODFLOW simulation model and the regression models will be completed with calibration to observed water level declines.
- A quantitative assessment is being conducted on how uncertainties and errors in the data affect the predictive models developed.
- The simulation and regression models will be used to make predictions about where and when availability problems may develop in the future for the area.

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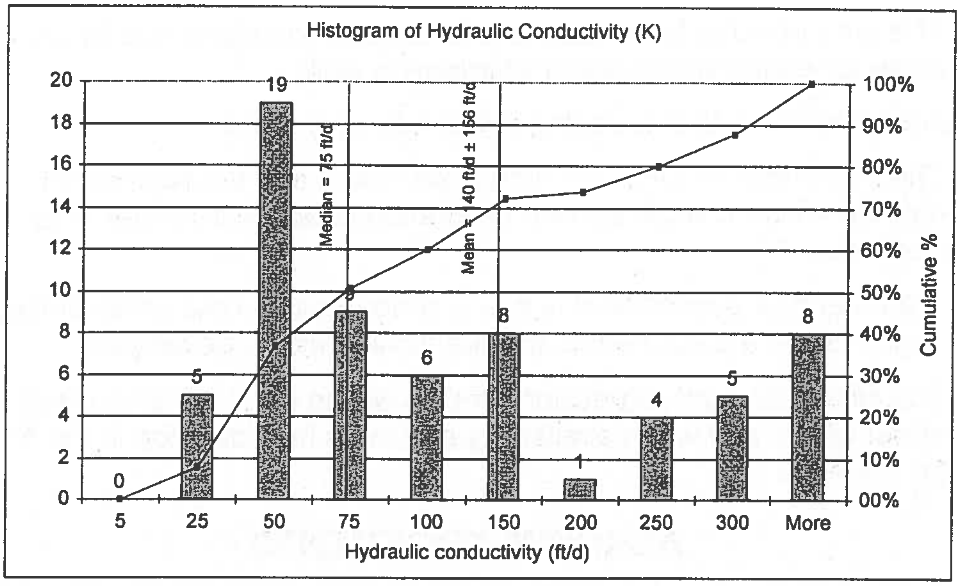

Figure 15. Histogram of hydraulic conductivity values from the GMD 4 area. Unpublished database compiled by Wayne Bossert of GMD 4. Median K value is 75 ft/d and mean K value is 140 ft/d ±156 ft/d.

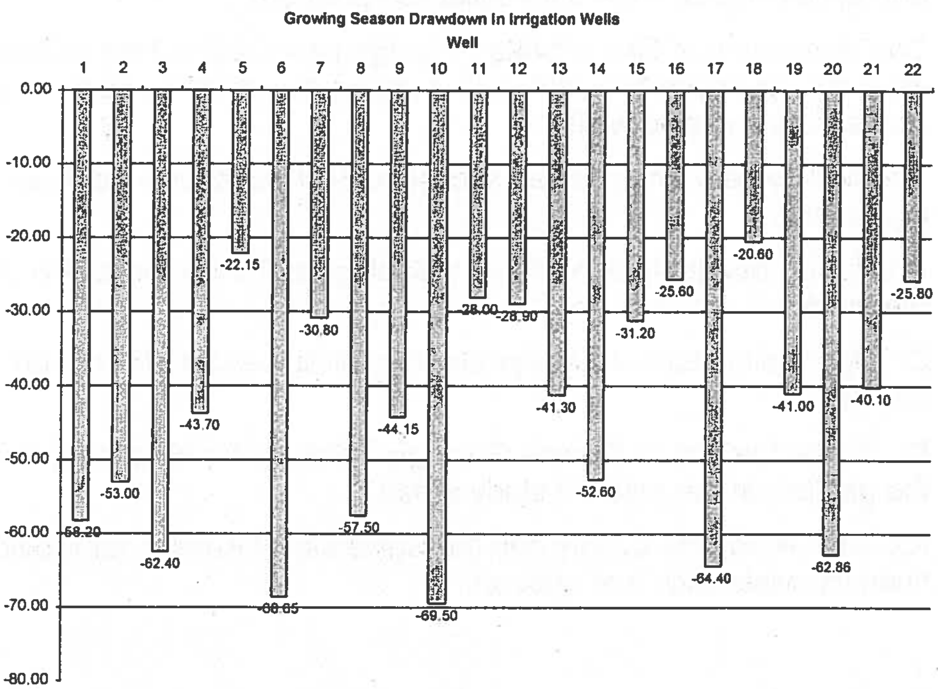

Figure 16. Growing season drawdowns in irrigation wells from the detailed study areas in Sheridan and Sherman counties.

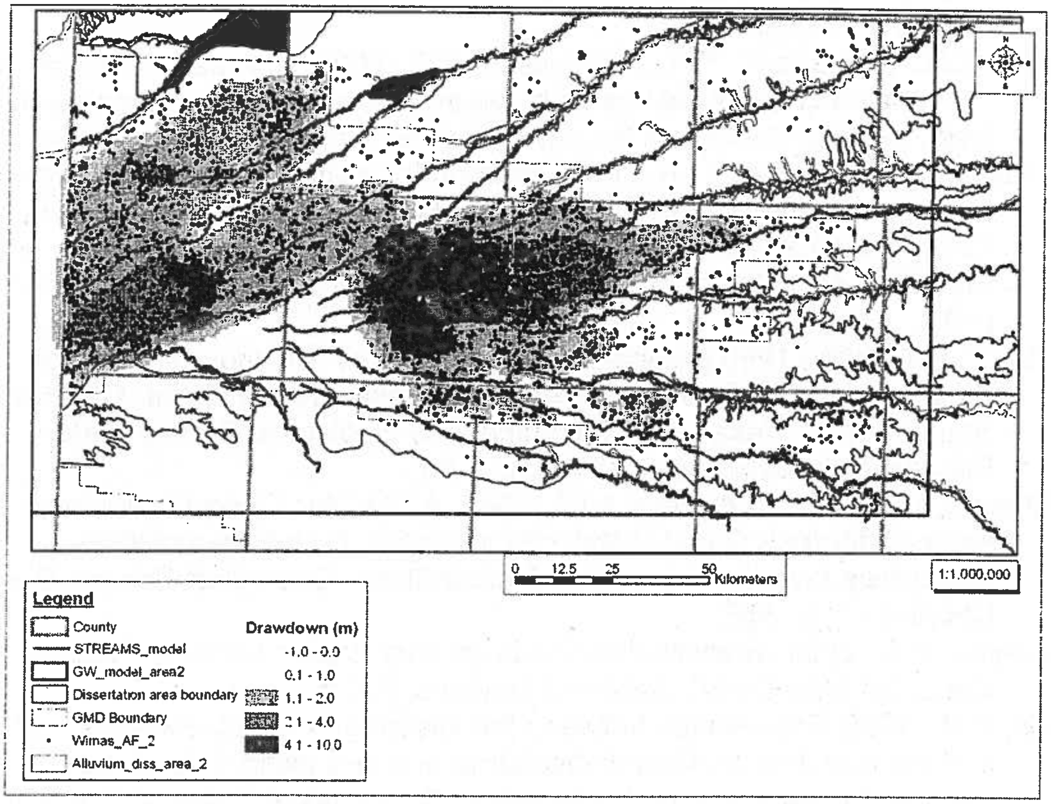

Figure 17. Simulated area of water level decline during irrigation season after 21 years of pumping.

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DESIGN AND MANAGEMENT CONSIDERATIONS FOR SUBSURFACE DRIP IRRIGATION SYSTEMS

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INTRODUCTION

If the goal of the irrigator is to develop and operate a successful subsurface drip irrigation (SDI) system, what is the purpose? Water conservation and water quality protection have often been cited as possible purposes to consider SDI. If so, it is imperative that the SDI system be designed and operated in a manner so that there is a realistic hope to satisfy those purposes. It should also be noted that an improperly designed SDI system is less forgiving than an improperly designed center pivot sprinkler system. Water distribution problems may be difficult or impossible to correct for an improperly designed SDI system.

The intent of this paper is <u>not</u> to show the producer how to step-by-step design and manage their SDI system. Rather, it is to discuss some of the concepts necessary in a properly designed and management system. The hope is this discussion will enable the producer to *<u>ask</u>* the right questions of those designing or selling them an SDI system. As with most any new technology in a region, there are unscrupulous individuals trying to take advantage of unknowledgeable buyers. These SDI systems could easily end in failure. At the same time there are many reputable distributors, sales people and installers that are trying to promote the successful use of SDI technology. System failures hurt all those involved with SDI, the enduser, the industry selling it, and the university and government entities promoting it. *<u>Don't be afraid to ask questions and to seek clarifications. Time spent now will be rewarded down the road.</u>*

HYDRAULIC DESIGN

A schematic of a typical SDI system showing the necessary components is shown in Figure 1. The actual requirements in equipment, their sizes and their location is dependant on the actual design, but elements of all these components should be present in all systems.

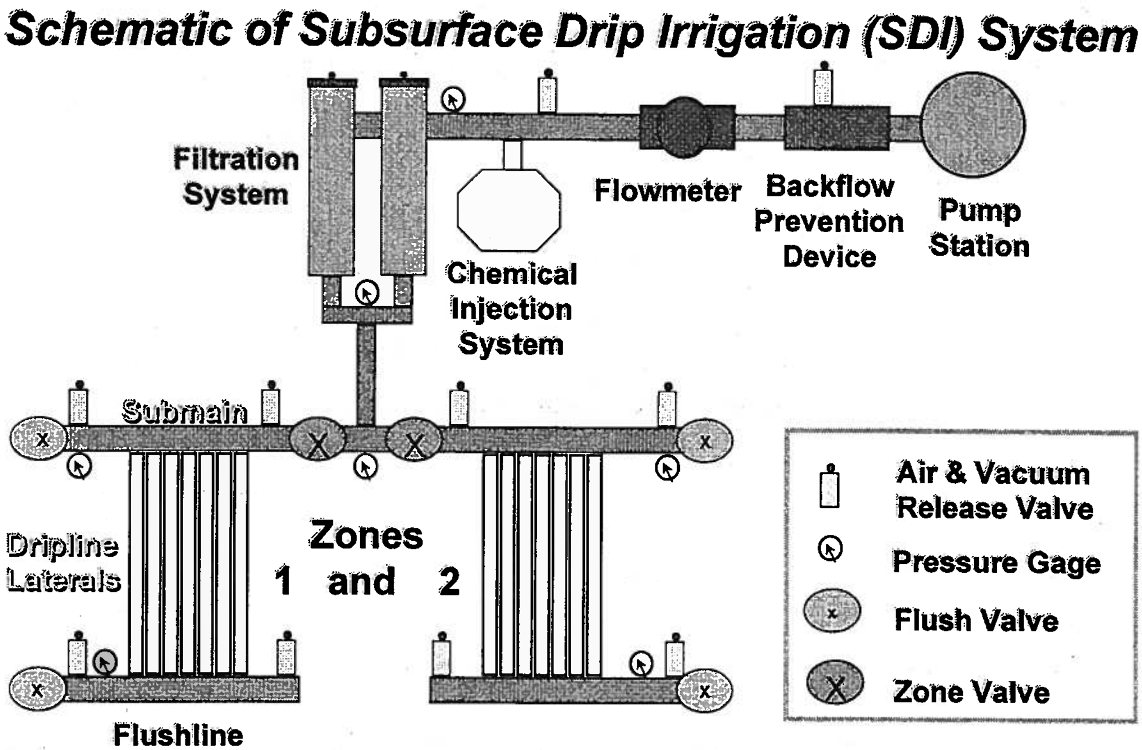

Figure 1. Component requirements of a SDI system.

Successful operation of a SDI system begins with a proper hydraulic design which satisfies constraints dictated by crop, soil type and characteristics, field size, shape, and topography, water source and supply. Disregarding design constraints will likely result in a system that is costly in both time and money to operate and will likely increase the chance of system failure. System failure might result in the loss of the total capital investment.

Crops and Soils Considerations

The crop and soil type will dictate SDI system capacity, dripline spacing, emitter spacing, and installation depth. The SDI system capacity must be able to satisfy the peak water requirement of the crop through the combination of the applied irrigation amount, precipitation, and stored soil water. The system capacity will influence the selection of the dripline flowrate and the zone size (area served by each submain). Improper selection of these items can result in more expensive systems to install and operate.

The dripline spacing is obviously an important factor in system cost, and economics suggest wider spacings. However, wide spacing will not uniformly supply crop water needs and will likely result in excess deep percolation on many soil types. The dripline spacing is dictated by the lateral extent of the crop root zone, lateral soil water redistribution, and in-season precipitation. Studies on silt loam soils in western Kansas conducted by Kansas State University have indicated that a 60-inch dripline spacing is optimal for a corn-row spacing of 30 inches. It may be feasible and logical to use a 72-inch dripline spacing for corn planted in 36-inch spaced corn rows. However, this might limit successful use of the system for crops grown in a narrow row pattern. A 72-inch dripline spacing would not be recommended in the Central Great Plains region for corn grown in a 30-inch row culture even though some dripline installers may recommend this as a way to cut investment costs. Soils that have a restrictive clay layer below the dripline installation depth might allow a wider dripline spacing without affecting crop yield. Wider spacings may also be allowable in areas of increased precipitation as the dependency of the crop on irrigation is decreased. The emitter spacing is dictated by the same factors affecting dripline spacing. However, generally, the emitter spacing is less than the dripline spacing. As a rule of thumb, dripline spacing is related to crop row spacing while emitter spacing is more closely related to crop plant spacing. One of the inherent advantages of a SDI system is the ability to irrigate only a fraction of the crop root zone. Careful attention to dripline spacing and emitter spacing are, therefore, key factors in achieving the purpose of water conservation and water quality protection.

The installation depth is also related to the crop and soil type. Deep installations reduce the potential for soil evaporation and also allow for a wider range of tillage practices. There may also be some reduced potential for chemical, biological and root clogging of the emitters for the deeper installations. However, deep installations may limit the effectiveness of the SDI system for germination and may restrict availability of surface-applied nutrients. Acceptable results have been obtained with depths of 16-18 inches in KSU studies in western Kansas on deep silt loam soils. Obtaining sufficient soil water for germination is not consistently possible at these depths on these silt loam soils with typical dripline capacities (gph/emitter or gpm/100 ft). The soil, the soil firmness, the dripline depth and the dripline capacity are just a few of the factors affecting soil water redistribution for germination. Many of these typical factors for SDI systems in the Great Plains work against obtaining water for germination. Some producers in the Central Great Plains region are opting for installations in the 12-14 inch depth range to give more flexibility in germination. However, in extreme years, such as 2002, this design feature may not be effective. Fortunately, in most years, we do not need to provide irrigation to germinate a summer crop in the Central Great Plains. Driplines should probably be installed above any restrictive clay layers that might exist in the soil. This would help increase lateral soil water redistribution. K-State initiated a research study to determine the optimum dripline depth (8, 12, 16, 20 or 24 inches) for long term corn production in 1999. The results from this study indicate that these dripline depths had very little effect on corn yields. Further research is needed to determine if depth may affect system longevity.

The orientation of driplines with respect to crop rows has not been a critical issue with SDI systems used for corn production on the deep silt loam soils. Traditionally, a parallel orientation is used. This may be advantageous in planning long term tillage, water, nutrient and salinity management schemes. However, K-State research has shown either parallel or perpendicular orientations are acceptable.

Field Size, Shape, and Topography

The overall field size may be limited by the available water supply and capacity. The ability to economically adjust the size of the irrigated field to the available water supply is a distinct advantage of SDI systems compared to center pivot sprinklers. If sufficient water supply is available, the field size, shape, and topography, along with the dripline hydraulic characteristics, will dictate the number of zones. Minimizing the number of necessary zones will result in a more economical system to install and operate.

Whenever possible, dripline laterals should be installed downslope on slopes of less than 2%. On steeper terrain, the driplines should be made along the field contour and/or techniques for pressure control should be employed.

Dripline Hydraulic Characteristics

Pressure losses occur when water flows through a pipe due to friction. These friction losses are related to the velocity of water in the pipe, the pipe inside diameter and roughness, and the overall length. The emitter flowrate (Q) can generally be characterized by a simple power equation

$$Q = k H^x$$

where k is a constant depending upon the units of Q and H, H is the pressure and x is the emitter exponent. The value of x is typically between 0 and 1, although values outside the range are possible. For an ideal product, x equals 0, meaning that the flowrate of the emitter is independent of the pressure. This would allow for high uniformity on very long driplines, which would minimize cost. An emission product with an x of 0 is said to be fully pressure compensating. An x value of 1 is noncompensating, meaning any percentage change in pressure results in an equal percentage change in flowrate. Many lay-flat drip tape products have an emitter exponent of approximately 0.5. A 20% change in pressure along the dripline would result in a 10% change in flowrate if the exponent is 0.5. As a rule of thumb, flowrates should not change more than 10% along the dripline in a properly designed system. Most manufacturers can provide the emitter exponent for their product. *Irrigators would be well advised to compare the emitter exponent among products and be wary of manufacturers that cannot provide this information.*

Friction losses increase with length (Figure 2). For this example, the dripline has a design flowrate of 0.25 gpm/100 ft. at 10 psi on a level slope. The variation in flows, Q_{var}, are 6, 16, and 29% for the 400, 600 and 800 ft. runs, respectively. Using general criteria for Q_{var}, these systems would be classified as desirable, acceptable, and not acceptable (Table 1). It should be noted that this example is based on 5/8 inch diameter dripline. Longer lengths of run would be obtainable with larger dripline diameters. The industry has responded well to the needs of the producer and are now producing larger dripline diameters. However, the producer is encouraged to carefully compare investment and anticipated management costs for the various dripline sizes before concluding what is the optimal dripline size for their installation. Larger diameters are not always more desirable, as they increase the filling and purging times for the system, which could affect water and chemical application uniformity.

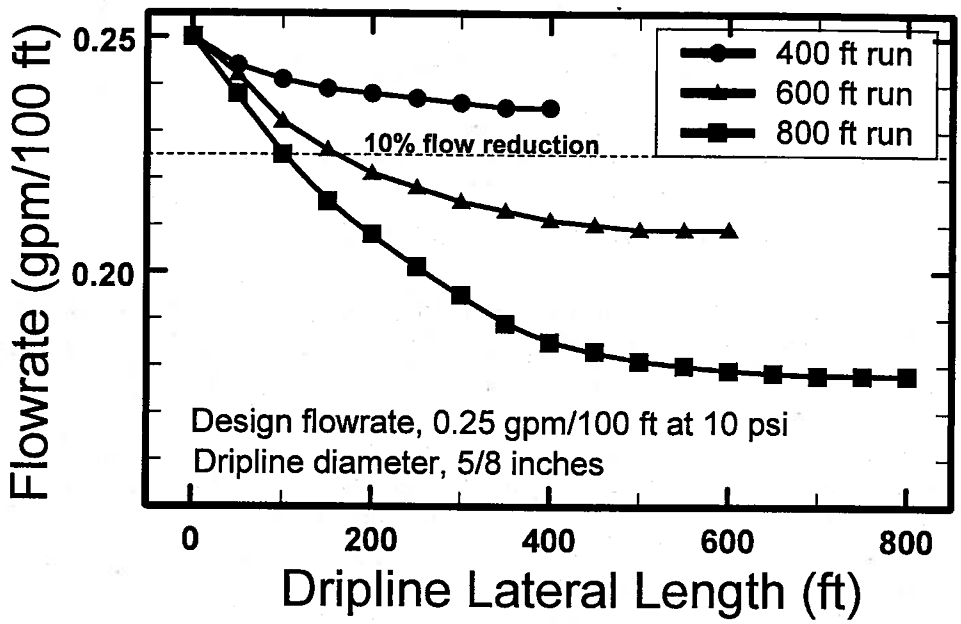

Figure 2. Calculated dripline flowrates on level slopes as affected by length of run. For this example dripline, only the 400 ft lateral length meets the desired criteria of maintaining flow variations less than 10%.

Table 1. Flow variation criteria for microirrigation systems. Adapted from Bralts, et al., 1987.

Flow variation, Qvar = 100 x ((Qmax -Qmin)/Qmax)	
Desirable	< 10%
Acceptable	10 - 20%
Unacceptable	> 20%

Friction losses also increase with the velocity of water in the dripline. For a given inside diameter of line, friction losses will be greater for driplines with higher flowrates (Figure 3). Some designers prefer higher capacity driplines because they are less subject to clogging and allow more flexibility in scheduling irrigation. However, if larger-capacity driplines are chosen, the length of run may need to be reduced to maintain good uniformity. Additionally, the zone area may need to be reduced to keep the flowrate within the constraints of the water supply system. Decreasing the length of run or the zone area increases the cost of both installation and operation.

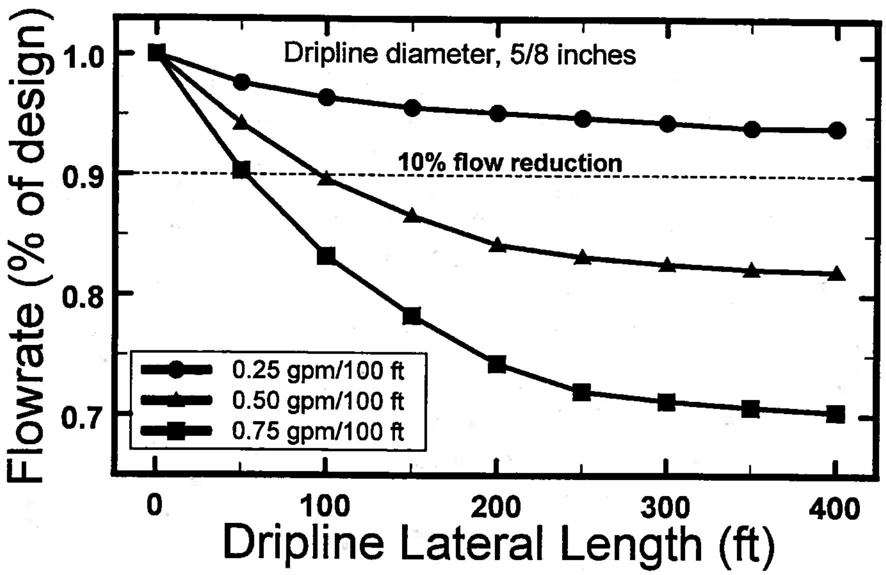

Figure 3. Calculated flowrates on level slopes as affected by dripline capacity. In this example only the 0.25 gpm/100 ft dripline capacity meets the desired criteria of maintaining flow variations less than 10%.

The land slope can have either a positive or negative effect on the pressure distribution along the dripline lateral (Figure 4). Irrigating uphill will always result in increasing pressure losses along the lateral length. If the downhill slope is too large, the flowrate at the end of the line may be unacceptably high. In the example shown, the most optimum slope is either 0.5 or 1.0% downslope. Both slopes result in a flowrate variation of approximately 10% for the 600 ft. run. If slopes are too great, there is the opportunity to run the driplines cross slope or along the contour. Pressure compensating emitters can also be utilized on greater slopes but may not be cost competitive for relatively low value crops such as corn.

The overall effect on uniformity is specific to the field slope, length of run, dripline capacity and diameter. Many of the manufacturers have computer programs that can quickly compare many design alternatives. The producer is encouraged to utilize this service to determine the overall effect on design his circumstances may dictate.

The preceding discussion has only dealt with theoretical calculations that don't take into account the variability in manufacturing. The coefficient of manufacturing variation, C_V, is a statistical term used to describe this variation. Some dripline products are inherently difficult to manufacture with consistency and, therefore, may have a high C_V. Other products may suffer from poor quality control. The American Society of Agricultural Engineers (ASAE) has established C_V ranges for line-source driplines. A C_V of less than 10% is considered good; from 10 to 20%, average; and greater than 20%, marginal to unacceptable. The C_V of a product should be obtained from the manufacturer to aid in decisions regarding suitability of the product for a particular installation.

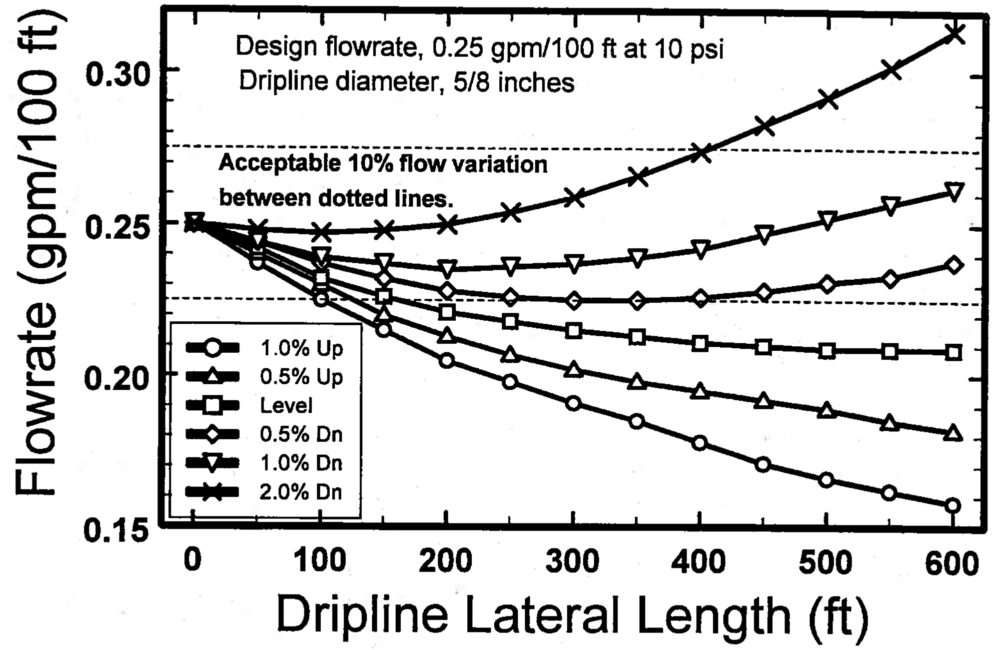

Figure 4. Calculated dripline flowrates as affected by slope. In this example, the 0.5 and 1.0% downslope dripline laterals meet the desired criteria of maintaining flow variations less than 10%.

There are two additional terms to describe system uniformity that can be calculated for a SDI system. They are the emission uniformity Eu and the statistical uniformity Us. The calculation of the terms lies beyond the scope of this discussion, but they may be encountered in the process of developing a SDI system. The criteria for evaluating these uniformities as developed by the ASAE are listed in Table 2. Many systems are now being designed on the basis of the design emission uniformity, Eu, so it is a good idea for producers to familiarize themselves with these criteria. There are other uniformity terms that are often mathematically related that could be used to design systems. If a producer encounters some other uniformity criteria, it would be wise for them to seek a clarification as to how those criteria might compare to those presented here (Table 1 and Table 2).

Table 2. Uniformity criteria established by ASAE Engineering Practice EP-405.

	Statistical Uniformity, Us	Emission Uniformity, Eu
Excellent	95-100%	94-100%
Good	85-90%	81-87%
Fair	75-80%	68-75%
Poor	65-70%	56-62%
Unacceptable	< 60%	< 50%

FILTRATION, FLUSHING, AND WATER TREATMENT

Clogging of the dripline emitters is the major cause of system failure. Clogging can be caused by physical, chemical, or biological materials. The filtration system is one of the most important components of the SDI system. Its operation and maintenance must be well understood by the irrigator to help ensure the longevity of the SDI system. A more complete K-State source on this topic is Alam et al. (1999). There are many different types of filtration systems. The type is dictated by the water source and also by emitter size. Improper filter selection can result in a SDI system which is difficult to maintain and a system prone to failure. The filtration system can be automated to flush at regular time intervals or at a set pressure differential.

Screen or sand media filters are used to remove the suspended solids such as silt, sand, and organic and inorganic debris. Surface water often requires more extensive filtration than groundwater, but filtration is required for all systems.

Chemical reactions in the water can cause precipitates, such as iron or calcium deposits to form inside the driplines and on the emission point. Clogging can be caused by either natural water conditions or by chemicals such as fertilizer added to the water. To avoid chemical clogging, the water must be analyzed to determine what chemicals are prevalent and which chemical additives should be avoided. Chemical water treatment may be required on a continuous or intermittent basis. Acids are sometimes used to prevent clogging and also to help renovate partially clogged driplines. The need for treatment is dictated by the water source and the emitter size. *A thorough chemical analysis of the water source should be made prior to development of the SDI system.*

Biological clogging problems may consist of slimes and algae. Some problems are eliminated in the filtration process, but injection of chlorine into the driplines on a periodic basis is required to stop the biological activity. The water source and composition will determine, to a large extent, the need for chlorination.

A flushing system is recommended at the distal end of the dripline laterals (Figure 1) to assist in removing sediment and other materials that may accumulate in the dripline during the season. This is in addition to a proper filtration system. A useful way to provide for flushing is to connect all the distal ends of the driplines in a zone to a common submain or header that is called the flushline. This allows the flushing to be accomplished at one point. Two other distinct advantages exist for this design feature. If a dripline becomes clogged or partially clogged, water can be provided below the clogged point by the interconnected flushline. Additionally, if a dripline break occurs, positive water pressure on both sides of the break will limit sediment intrusion into the line. Generally, a minimum flow velocity of 1-2 ft/second is considered adequate for flushing dripline laterals. This flow velocity requirement may often require careful sizing of the mains, submains, flushline mains, and valving.

MANAGEMENT CONSIDERATIONS

A thorough discussion of the management for SDI systems lies beyond the scope of this paper. However, a brief discussion with regards to system longevity and also with regards to satisfying the stated purposes is in order.

Managing a SDI system is not necessarily more difficult than managing a furrow or sprinkler irrigation system, but it does require a different set of management procedures. Improper management of a SDI system can result in system failure, which might mean the loss of the total capital investment. Proper day-to-day management requires the operator to evaluate the component performance, to determine crop irrigation needs, and to make adjustments as needed. The performance of the SDI system components can be evaluated by monitoring the flowrate and pressures in each zone. Pressure gages should be installed on riser pipes from the submain and flushline at each of the four corners of the zone. Comparison of the flowrate and pressures from one irrigation event to the next can reveal any problems that are occurring. For instance, if the flowrate has increased and the pressure is lower, the irrigator needs to investigate for a possible leak in the system. Conversely, if the flowrate is lower and the pressure is higher, the irrigator needs to check the filtration system or look for possible clogging. Disregarding day-to-day management can result in problems such as poor water distribution, low crop yields, and even system failure.

SDI systems are typically managed to frequently apply small amounts of water to the crop. If properly managed, there are opportunities to save water and to provide a more consistent soil water environment for the crop. However, irrigation scheduling must be employed as some of the visual indicators of overirrigation, such as runoff, no longer exist with this type of irrigation. Overirrigation with a SDI system can lead to reduced yields because of aeration problems exacerbated by the higher irrigation frequency and also perhaps by the more concentrated crop root system. Overirrigation can dramatically increase deep percolation, which can increase groundwater contamination.

SDI systems are often used to provide all or a portion of the crop nutrient needs. The ability to spoon feed the crop its nutrients throughout the season reduces the potential for groundwater contamination. However, fertigation is only recommended on SDI systems with good or excellent uniformity. Irrigation and nutrient amounts must be managed together to prevent leaching.

CONCLUDING STATEMENT

The initial investment costs for a SDI system are high. Efforts are justified to minimize, investment costs whenever possible and practical. However, if water conservation and water quality protection are important, proper design procedures must be employed. The SDI system must also be properly designed to ensure system longevity. Minimizing investment costs through cheaper designs can be a double-edged sword, as a cheaper system may increase operating costs and/or possibly increase the chance of system failure.

K-State continues to develop appropriate methodology for successful utilization of SDI technology in the US Central Great Plains. Much of this technology is summarized on the K-State SDI website which can be accessed by pointing your Internet web browser to **http://www.oznet.ksu.edu/sdi/**

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. See www.oznet.ksu.edu/sdi/Reports/2002/sysreq.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.

SDI can be a viable irrigation system option, but should be carefully considered.

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Center Pivot Sprinkler and SDI Economic Comparisons

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INTRODUCTION

In much of the Great Plains, the rate of new irrigation development is slow or zero. However, as the farming populace and irrigation systems age, there has been a continued momentum for conversion of existing furrow-irrigated systems to modern pressurized irrigation systems. These systems, including center pivot sprinkler irrigation (CP) and subsurface drip irrigation (SDI), can potentially have higher irrigation efficiency and irrigation uniformity while at the same time reducing irrigation labor. SDI is a relatively new irrigation system alternative for corn production on the Great Plains. Producers converting from furrow-irrigated systems to a pressurized system are faced with economic uncertainty about whether to convert to center pivot sprinklers (CP) or SDI. This paper presents economic comparisons of CP and SDI and the sensitivity of these comparisons to key factors. A Microsoft Excel[1] spreadsheet template also will be introduced for making these comparisons.

ANALYSES METHODS AND ECONOMIC ASSUMPTIONS

Field & irrigation system estimates

An existing furrow-irrigated field with a working well and pumping plant is being converted to either center pivot sprinkler irrigation or SDI. The pumping plant is located at the center of one of the field edges and is at a suitable location for the initial SDI distribution point (i.e. upslope of the field to be irrigated). Any necessary pump modifications (flow and pressure) for the CP or SDI systems are assumed to be of equal cost and thus are not considered in the analysis.

Land costs are assumed to be equal across systems for the overall field size with no differential values in real estate taxes or in any government farm payments. Thus these factors "fall out" or do not economically affect the analyses.

An overall field size of 160 acres (square quarter section) was assumed for the base analysis. This overall field size will accommodate a 125 acre CP system and a 155 acre SDI system. It was assumed that there would be 5 noncropped acres consumed by field roads and access areas. The remaining 30 acres under the CP system are available for dryland cropping systems.

Irrigation system costs were obtained from KSU estimates (O'Brien et al., 2001). The 125 acre CP system was assumed to cost $48,375 or $387.00/irrigated acre, while the 155 acre SDI system was assumed to cost $126,015 or $813/irrigated acre. In the base analyses, the life for the two systems are assumed to be 25 and 15 years for the CP and SDI systems, respectively. No salvage value was assumed for either system. This assumption of no salvage value may be inaccurate, as both systems might have a few components that may be reusable or available for resale at the end of the system life. However, relatively long depreciation periods of 15 and 25 years makes the zero salvage value a minor issue in the analysis.

When the overall field size decreases, thus decreasing system size, there are large changes in cost per irrigated acre between systems. SDI costs are nearly proportional to field size, while CP costs are not proportional to field size (Figure 1). Quadratic equations were developed to calculate system costs when less than full size 160 acre fields were used in the analysis:

$$\text{CPcost\%} = 44.4 + (0.837 \times \text{CPsize\%}) - (0.00282 \times \text{CPsize\%}^2) \qquad \text{(Eq. 1)}$$

$$\text{SDIcost\%} = 2.9 + (1.034 \times \text{SDIsize\%}) - (0.0006 \times \text{SDIsize\%}^2) \qquad \text{(Eq. 2)}$$

where CPcost% and CPsize%, and SDIcost% and SDIsize% are the respective cost and size % in relation to the full costs and sizes of irrigation systems fitting within a square 160 acre block.

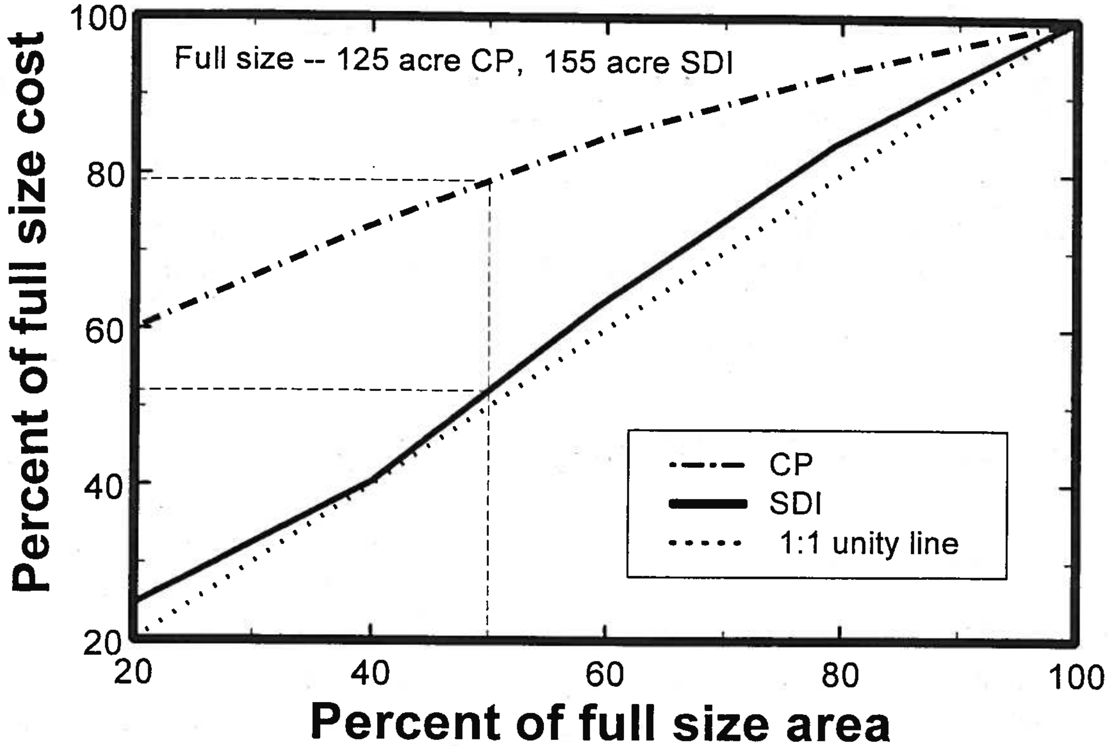

Figure 1. CP and SDI system costs as related to field size. (O'Brien et al., 1997)

Investment interest costs were assumed to be 8% and total interest costs were converted to an average annual interest cost for this analysis. Annual insurance costs were assumed to be 0.25% of each total system cost. It is unclear whether insurance can be obtained for SDI systems and if SDI insurance rates would be lower or higher than CP systems. Many of the SDI components are not subject to the climatic conditions that are typically insured hazards for CP systems. However, system failure risk is probably higher with SDI systems which might influence any obtainable insurance rate.

A summary of field and system estimates is provided in Table 1.

Table 1. Field description and irrigation system estimates

	Total	CP	SDI
Field area, acres	160	125	155
Non-cropped field area (roads and access areas), acres	5	-	-
Cropped dryland area, acres		30	0
Irrigation system investment cost, total $		$48,375	$126,015
Irrigation system investment cost, $/irrigated acre		$387	$813
Irrigation system life, years		25	15
Interest rate for investment, %	8		
Annual Insurance rate, % of total system cost		0.25	0.25

Production cost estimates

The following economic analysis expresses the results as an advantage or disadvantage of CP systems over SDI in net returns to land and management. Thus, many fixed costs do not affect the analysis and can be ignored. Additionally, the analysis does not indicate if either system is ultimately profitable for corn production under the assumed current economic conditions.

Production costs are adapted from KSU estimates (Dumler, et al., 2001). CP variable costs are estimated to be $334.73/acre in the baseline analysis while SDI variable costs are slightly lower at $319.47/acre. The reduction in variable costs for SDI is attributable to an assumed 25% net water savings that is consistent with research findings by Lamm et al., 1995. This translates into a 17 and 13 inch gross application amount for CP and SDI, respectively, for this analysis. The estimated production costs (Table 2.) are somewhat high considering the gross revenues are only approximately $500/irrigated acre. This may be reflecting the overall profitability issue during these economic conditions, but producers might also try to reduce these variable costs somewhat to cope with low crop prices. This fact is pointed out because a lowering of overall variable costs favors SDI, since more irrigated cropped acres are involved, while higher overall variable costs favors CP production. The variable costs for both irrigation systems represent typical practices for western Kansas.

Table 2. Variable costs factors for corn using CP and SDI.

Factor	CP	SDI
Corn seeding rate, seeds/acre	30000	30000
Corn seed costs at $1.16/1000 seeds, $/acre	$34.80	$34.80
Herbicide, $/acre	$30.48	$30.48
Insecticide, $/acre	$38.54	$38.54
Nitrogen fertilizer, lb/acre	225	225
Nitrogen fertilizer at $0.13/lb, $/acre	$29.25	$29.25
Phosphorus fertilizer, lb/acre	45	45
Phosphorus fertilizer at $0.22/lb, $/acre	$9.90	$9.90
Crop consulting, $/acre	$6.50	$6.50
Custom hire/machinery expenses, $/acre	$105.00	$105.00
Irrigation labor, $/acre	$5.00	$5.00
Irrigation amounts, inches	17	13
Fuel and oil for pumping, $/inch	$3.34	$3.34
Fuel and oil for pumping, $/acre	$56.78	$43.42
Irrigation maintenance and repairs, $/inch	$0.33	$0.33
Irrigation maintenance and repairs, $/acre	$5.61	$4.29
1/2 year interest on variable costs with 8% rate	$12.87	$12.29
Total Variable Costs	**$334.73**	**$319.47**

Yield and revenue stream estimates

Corn grain yield was estimated at 210 bushels/acre in the base analysis and a corn selling price of $2.35/bushel. Net returns for the 30 cropped dryland acres for the CP system (corners of field) were assumed to be $32.50/acre which is essentially the current dryland crop cash rent estimate for Northwest Kansas. Government payments related to irrigated crop production are assumed to be spread across the overall field size and thus do not affect the economic comparison of systems.

Sensitivity analyses

In any economic analyses the results depend greatly on the initial economic assumptions. In this analyses, changes in the economic assumptions can affect which system is most profitable and by how much. Thus, a major effort of this paper as indicated in the title was to examine the economic sensitivity of the baseline results to key economic factors. The factors examined were:

- Size of CP irrigation system
- Shape of field (full vs. partial circle CP system)
- Life of SDI system
- SDI system cost
- Any additional production cost savings with SDI
- Corn yield
- Corn price
- Yield/price combinations
- Yield advantage for SDI

Microsoft Excel spreadsheet template

A Microsoft Excel[1] spreadsheet template was created to perform the economic analyses. Additionally, this template can serve as an easy tool for users to perform their own comparisons using their own estimates. The template has five worksheets, the Main, CF, Field size & SDI life, SDI cost & life, Yield & price tabs. Most of the calculations and the result are shown on the Main tab (Figure 2.). The Main tab requires 18 user inputs to perform the comparison. However, current KSU suggestions are indicated for all 18 inputs in case the user does not have a better estimate. The user is responsible for entering and checking the values in the unprotected input cells. All other cells are protected on the Main tab. Some error checking exists on overall field size and some items (e.g. overall results and cost savings) are highlighted differently when different results are indicated. The CF tab represents the costs of production and is provided to the user for informational purposes. It is suggested to the user that rather than changing the baseline assumptions on the CF tab, the user should just input differential production costs between the systems on the Main tab. This will help maintain integrity of the baseline production cost assumptions. KSU plans to maintain the CF tab and update it at least annually. The essence of the CF tab is represented by Table 2. The last three tabs are sensitivity analyses for selected key factors. Figures 3, 4, and 5 restate most of the results of these three additional tabs in graphical form. These sensitivity analysis tabs automatically update when different assumptions are made on the Main tab.

This template determines the economics of converting existing furrow-irrigated fields to center pivot sprinkler irrigation (CP) or subsurface drip irrigation (SDI) for corn production.

Version 03, modified by F.R. Lamm, 1-12-03

Field description and irrigation system estimates	Total	Suggested	CP	Suggested	SDI	Suggested
Field area, acres	160 ←	160	125 ←	125	155 ←	155
Non-cropped field area (roads and access areas), acres	5 ←	5				
Cropped dryland area, acres (= Field area - Non-cropped field area - Irrigated area)			30		0	
Irrigation system investment cost, total $			$48,375.00 ←	$48,375	$126,015.00 ←	$126,015
Irrigation system investment cost, $/irrigated acre			$387.00		$813.00	
Irrigation system life, years			25 ←	25	15 ←	15
Interest rate for system investment, %	8% ←	8%				
Annual insurance rate, % of total system cost			0.25% ←	0.25%	0.25% ←	0.25%
Production cost estimates			CP	Suggested	SDI	Suggested
Total variable costs, $/acre (See CF Tab for details on suggested values)			$334.73 ←	$334.73	$319.47 ←	$319.47
Additional SDI variable costs (+) or savings (-), $/acre			Additional Costs →		$0.00 ←	$0.00
Yield and revenue stream estimates		Suggested	CP	Suggested	SDI	Suggested
Corn grain yield, bushels/acre			210 ←	210	210 ←	210
Corn selling price, $/bushel	$2.35 ←	$2.35				
Net return to cropped dryland area of field ($/acre)	$32.50 ←	$32.50				
Advantage* of CP over SDI, $/total field each year	**$3,612.30**					
$/acres each year	**$22.58**	* Advantage in *Net returns to land and management*				

Figure 2. *Main* worksheet (tab) of CP_SDI Excel template used to compare CP and SDI for corn production. Available for free at http://www.oznet.ksu.edu/sdi/ on the SDI software page.

RESULTS AND DISCUSSION OF THE ECONOMIC ANALYSES

Baseline analysis

Using the baseline assumptions (Table 1 and Table 2), the CP system has a $3,612.30/year ($22.58/acre-year) advantage over the SDI system (Figure 2.) These results match the general conclusions of O'Brien et al., 1998 indicating that CP systems generally have an advantage for large field sizes. Although, SDI systems can generate more gross revenue by having a higher percentage of irrigated acres in a given field, the much lower cost and longer assumed system life for full sized 125 acre CP systems offsets the higher SDI revenue advantage.

Sensitivity to field and irrigation system assumptions

The economic comparison is very sensitive to the size of the CP system and to the shape of the field (full vs. partial circle CP system). Smaller CP systems and systems which only complete part of the circle are less competitive with SDI than full size 125 acre CP systems (Figure 3). This is primarily because the CP investment costs ($/ irrigated acre) increase dramatically as field size decreases (Figure 1) or when the CP system cannot complete a full circle.

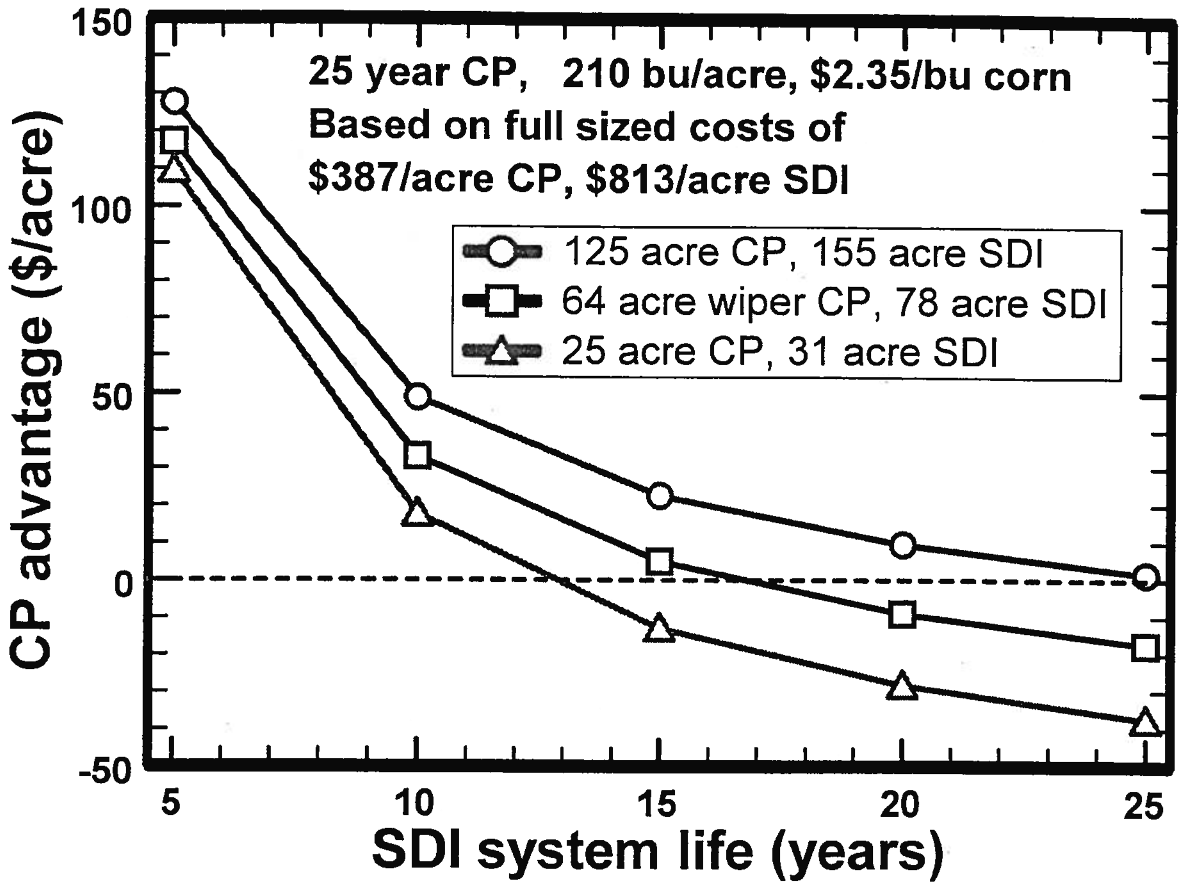

Figure 3. CP economic advantage as affected by field size, shape, and SDI system life.

The economic comparison is also very sensitive to life of the SDI system and to the SDI system cost (Figures 3 and 4). Increased longevity for SDI systems is probably the most important factor for SDI to gain economic competitiveness with CP systems. Conversely a short SDI system life that might be caused by early failure due to clogging, indicates a huge economic disadvantage that must be avoided. The sensitivity of CP system life and cost is much less (data not shown) because of the much lower initial CP cost and the much longer assumed life. In areas where CP life might be much less than 25 years due to corrosive waters, a sensitivity analysis with shorter CP life is warranted.

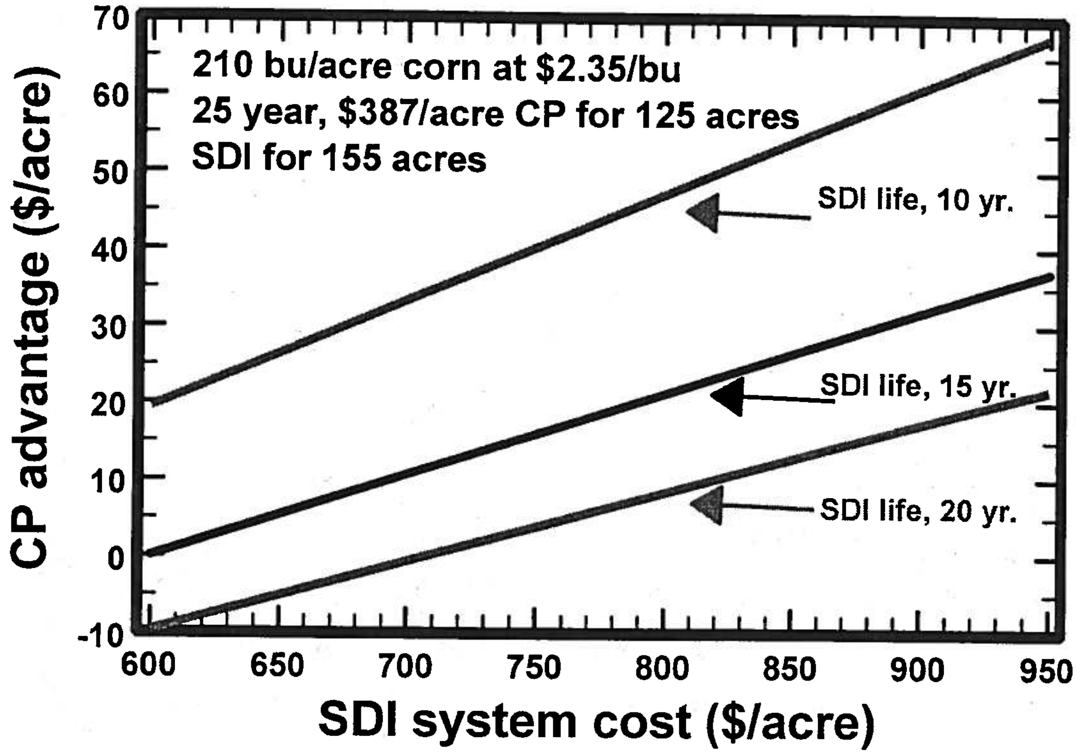

Figure 4. CP economic advantage as affected by SDI system life and cost.

Sensitivity to production cost estimates

The economic comparison is very sensitive to any additional cost savings with SDI (Figure 5). It should be noted that the present baseline analysis already assumes a 25% water savings with SDI. There are potentially some other production cost savings such as fertilizer and herbicides that have been reported for some crops and some locales. Small changes in the assumptions can make a sizable difference.

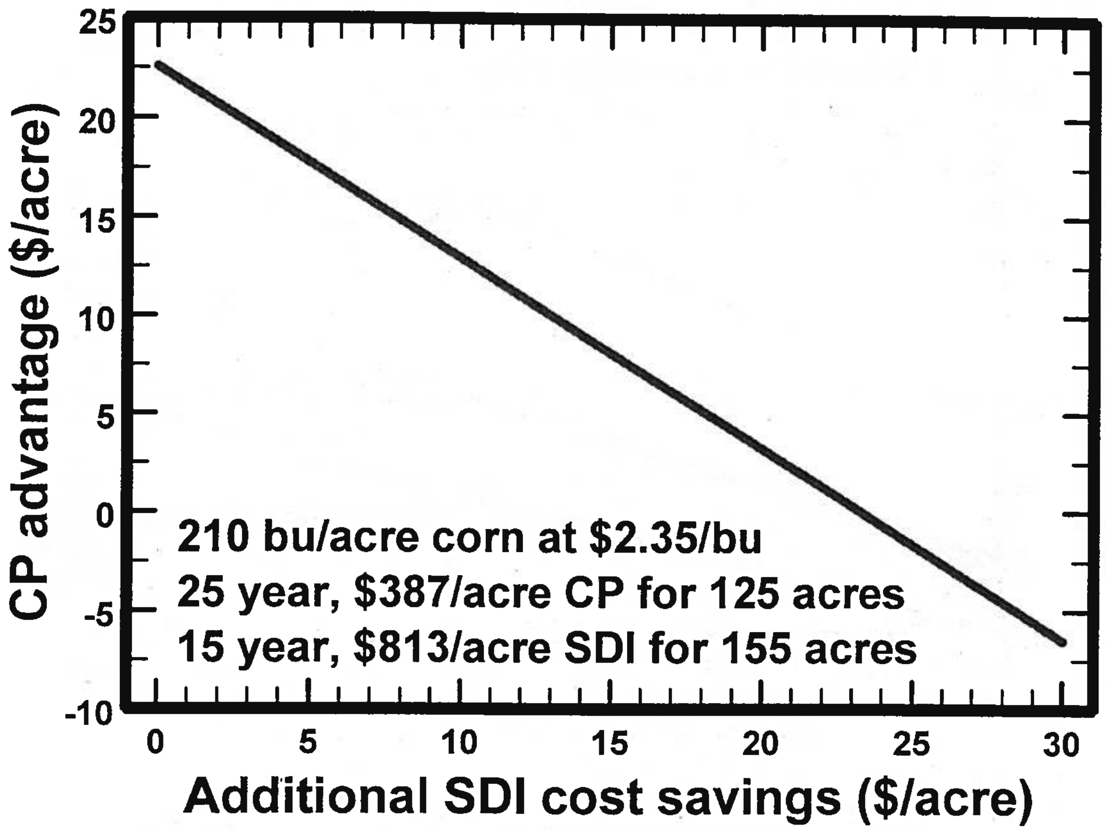

Figure 5. CP economic advantage as affected by additional SDI production cost savings.

Sensitivity to yield and revenue stream estimates

The economic comparison is moderately sensitive to corn yield and price and yield/price combinations and is very sensitive to any yield advantage for SDI. Higher yields and higher corn prices allow SDI to become more economically competitive with CP systems (Figure 6.). Combining a higher overall yield potential with an additional small yield advantage for SDI can allow SDI to be very competitive with CP systems (Figure 7.).

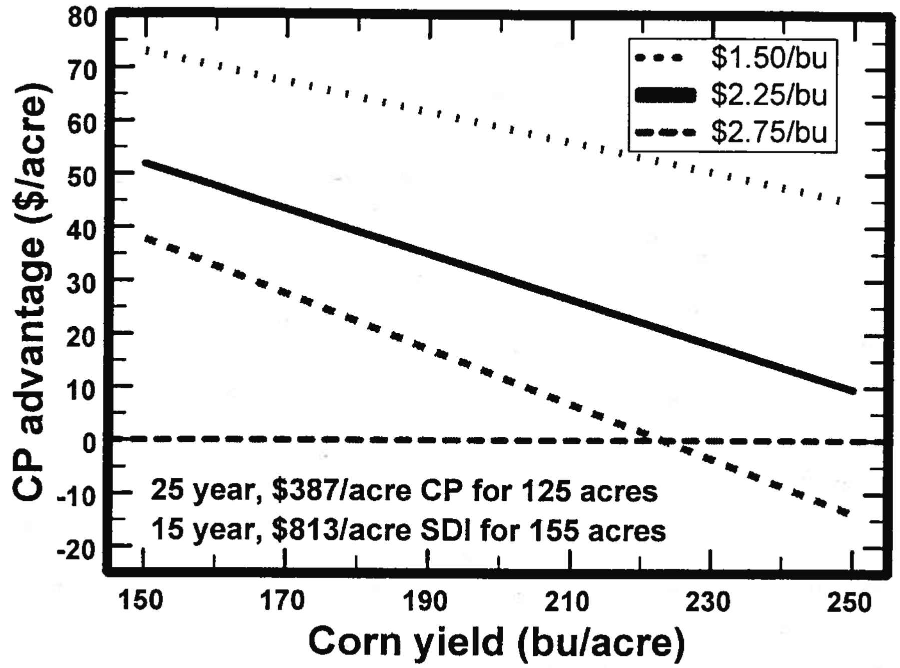

Figure 6. CP economic advantage as affected by corn yield and price.

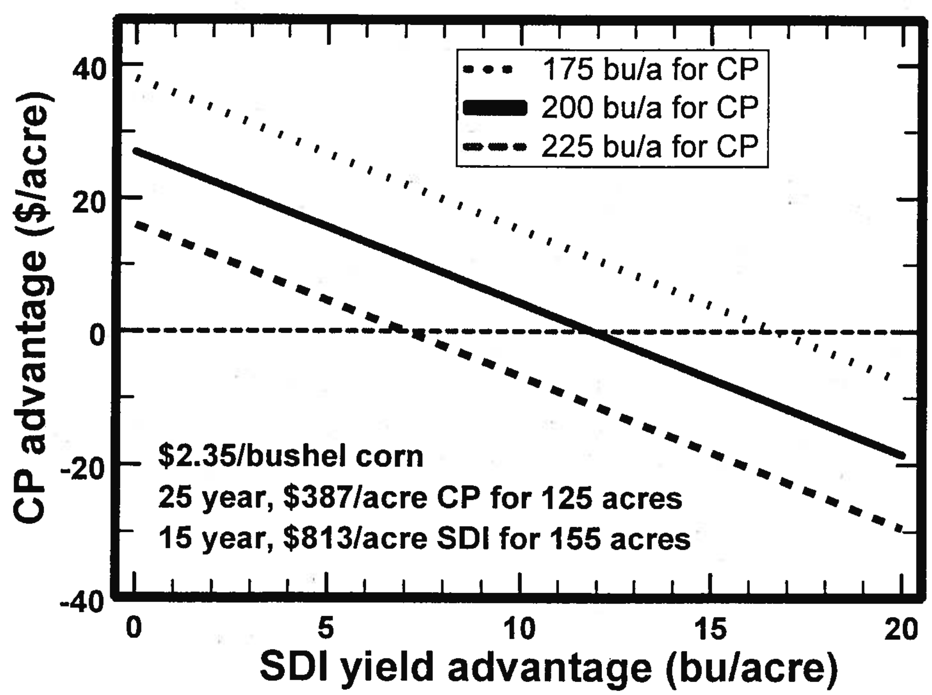

Figure 7. CP economic advantage as affected by overall corn yield potential and SDI yield .

CONCLUSIONS

Economic comparisons of CP and SDI systems are sensitive to the underlying assumptions used in the analysis. These results show that these comparisons are very sensitive to

- Size of CP irrigation system
- Shape of field (full vs. partial circle CP system)
- Life of SDI system
- SDI system cost

with advantages favoring larger CP systems and cheaper, longer life SDI systems.

The results are very sensitive to

- any additional production cost savings with SDI

The results are moderately sensitive to

- corn yield
- corn price
- yield/price combinations

and very sensitive to

- higher potential yields with SDI

with advantages favoring SDI as corn yields and price increase.

The results obtained here might differ drastically from those obtained from using your own assumptions. A Microsoft Excel spreadsheet template has been developed to allow producers to make their own comparisons. It is available on the SDI software page of the KSU SDI website at http://www.oznet.ksu.edu/sdi/.

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[1] *Mention of tradename is for informational purposes and does not constitute endorsement by Kansas State University.*

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FILTRATION: A BASIC COMPONENT FOR SDI TO AVOID CLOGGING HAZARDS

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The major cause of failures in Subsurface Drip Irrigation (SDI) and other microirrigation systems worldwide is clogging. The emitters in SDI systems are small, leaving a small margin for error, so it is important to understand the filtration and maintenance requirements of SDI systems and take a proactive approach to the prevention of clogging. Fortunately, most SDI users in the Great Plains are pumping high-quality groundwater, such as from the Ogallala Aquifer. This reduces the potential for clogging. Even so, proper steps must be taken to prevent clogging and maintain effective SDI system operation. With proper selection of a filtration system and maintenance, SDI can be used with surface water and other low-quality waters. Prevention of clogging and proper maintenance of the SDI system start before it is installed. Chemical and biological analysis of the irrigation water will help in filter selection, and indicate measures required to prevent clogging. The drip tube requirements, emitter-opening size in particular, may play a role in the selection of the filtration system to use. Proper placement and use of flow meters and pressure gauges are required to provide feedback to the system operator. Monitoring the flow meters and pressure gauges over time can reveal system performance anomalies that may require attention. Air vents, check valves, and vacuum relief valves may be required at various places in the system to prevent entry of chemically treated water into the water source and soil particles into the drip tapes. Also, flush lines are required to occasionally remove the material accumulated in the drip tapes. These basic components are shown in Figure 1, and a cut away diagram of a typical emitter is shown in Figure 2. Clogging hazards for SDI systems, regardless of the water source, fall into three general categories: physical, chemical, and biological. This article will discuss prevention of clogging

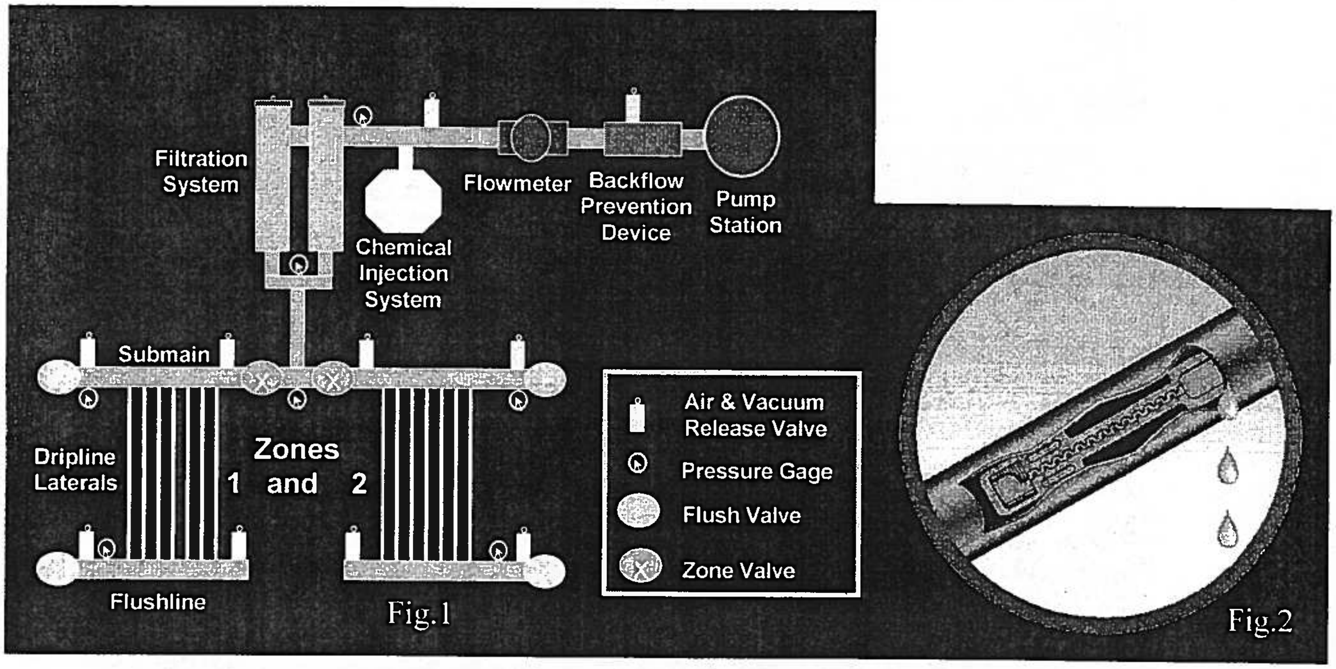

Figure 1 and 2: Schematic layout of a system and cut away diagram of an emitter

problems in these three categories with special emphasis on how they apply to SDI systems in the Great Plains.

Physical clogging hazards

Wells may produce sands that pose a threat of physical clogging of the emitters. Physical clogging hazards are usually removed with screen filters (Figure 3). Sizing of screen filters is based on the maximum particle size allowable according to emitter opening, quality of the irrigation water, the flow amount between required cleanings, and the allowable pressure drop across the filter. The maximum allowable particle size should be available from the drip tape manufacturer. If not, a rule of thumb is to use 0.1 times the smallest diameter in the emitters used. A 200-mesh screen filter will remove the fine sand and larger particles (larger than 75 microns or 0.003 inches), and is usually adequate for SDI systems using groundwater in the Great Plains. (Table 1 and 2).

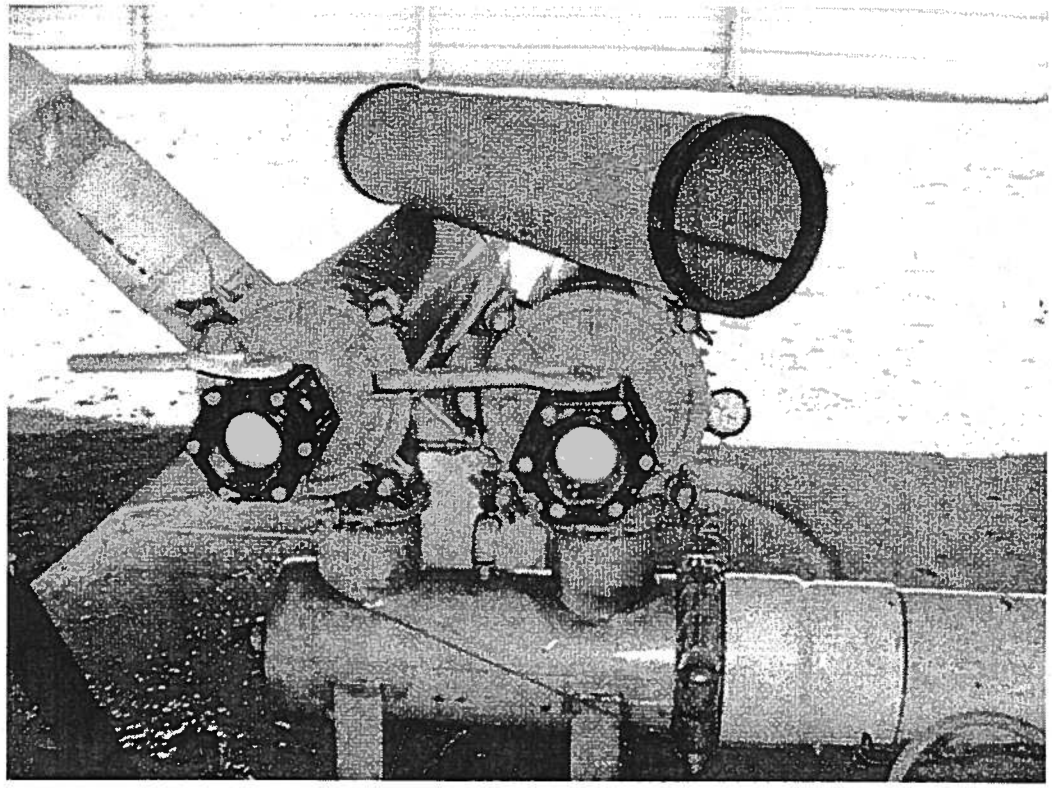

Figure 3: Screen filter showing installed system and a screen on top for display

Table 1. Screen Filter Opening Sizes

Mesh	Inches	Mm	Microns
40	0.017	0.425	425
100	0.006	0.150	150
150	0.004	0.105	105
200	0.003	0.075	75
270	0.002	0.053	53
400	0.0015	0.038	38

Table 2. Selected Equivalent Diameters

Particle	Diameter, mm
Coarse sand	0.50 to 1.00
Fine sand	0.10 to 0.25
Silt	0.002 to 0.05
Clay	<0.002
Bacteria	0.0004 to 0.002
Virus	<0.0004

Flow rates through screen filters should not exceed 200 gallons per minute per square foot of effective filter area. The effective filter area is defined as the area

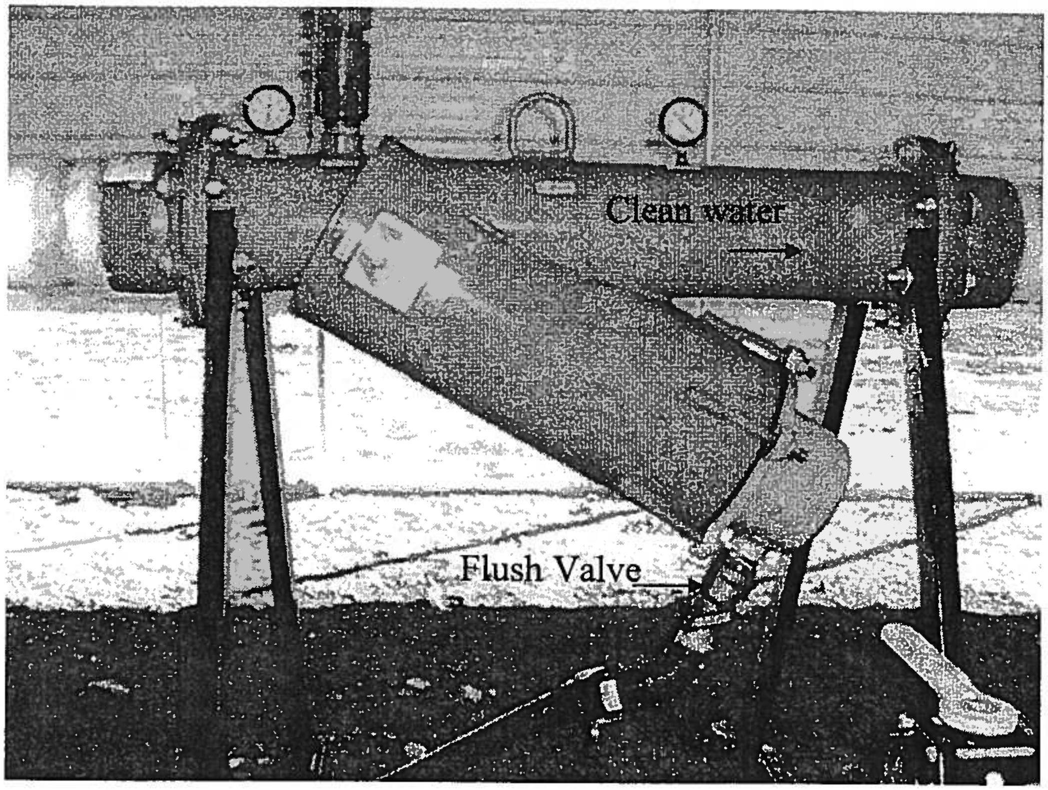

Figure 4: Spin filter in use in Western Kansas

of the openings in the filter screen. A 200-mesh screen has 200 openings in a linear inch. Generally, a 200-mesh screen area of 2.8 square feet will provide 1 square foot of effective filter area. Screen filters should be cleaned (back flushed) when the pressure drop across the filter increases by 3 to 5 psi, or as recommended by the manufacturer. Automatic flushing is available on some filtration systems. Also available are self-cleaning screen filters called "spin filters." These are continuous-flushing units. They swirl the water inward. Filtered particles move to the bottom of the filter and eventually leave the bottom of the filter through an opening to the outside (Figure 4). A small amount of water is continuously pushing the filtered particles out of the system and is removed from the irrigation system. Many producers use spin and screen filters as a combined set up. If large amounts of sand are in the water, a sand separator (also called a vortex sand separator or cyclone sand separator) may be required. Sand separators swirl the water and the centrifugal force separates the sand and other heavy particles from the water. If the amount of sand in the irrigation water is small, screen filtering will usually be adequate and a sand separator will not be required. For surface water, other steps may be required. For water with a large silt concentration, a settling basin may be required to remove the silt. For surface water, pre-screening of the water to remove debris such as stalks, leaves, and other plant residue may be required. When surface water is used for SDI, more extensive filtration systems such as media or disk filters may be desirable.

Biological clogging hazards

Sand media filters (Figure 5) are commonly used to filter organic materials. The effective sand size of the media is selected according to the desired degree of filtration. (Table 3).

Table 3. Sand Media Size and Screen Mesh Equivalent

Sand No.	Effective Sand Size (in)	Screen Mesh Size
8	0.059	70
11	0.031	140
16	0.026	170
20	0.018	230
30	0.011	400

Flow rates for media filters should not exceed approximately 25 to 28 gpm per square foot of filter surface area. Lower flow rates should be used with water sources containing greater than 100 ppm of suspended material, to reduce the need for frequent back flushing. Media filters should be back flushed when the pressure drop reaches about 10 psi, or as recommended by the filtration system manufacturer. Use of two filters in parallel allows back flushing of one filter while the other is actively filtering the water. Back flushing flow rates depend on the media size; lower flow rates should be used for finer filter media. Automatic flushing is generally required on media filtration systems. Some manufacturers

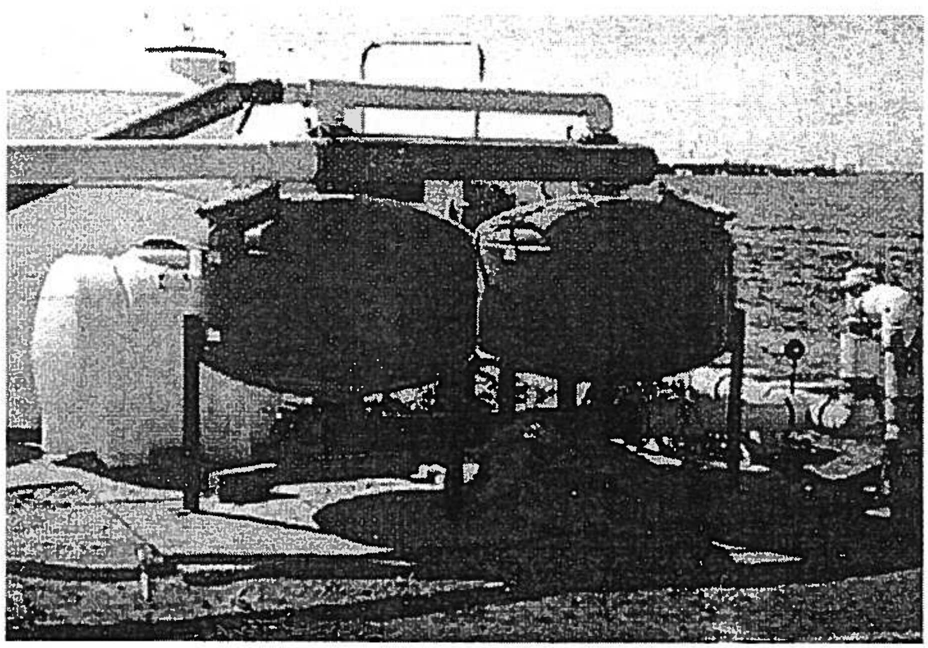

Figure 5: Sand media filter

recommend the use of a screen filter after the media filter to reduce the hazard of runaway media clogging the SDI system should a catastrophic failure of the media filtration system occur. Disk filters (Figure 6) are sometimes used.

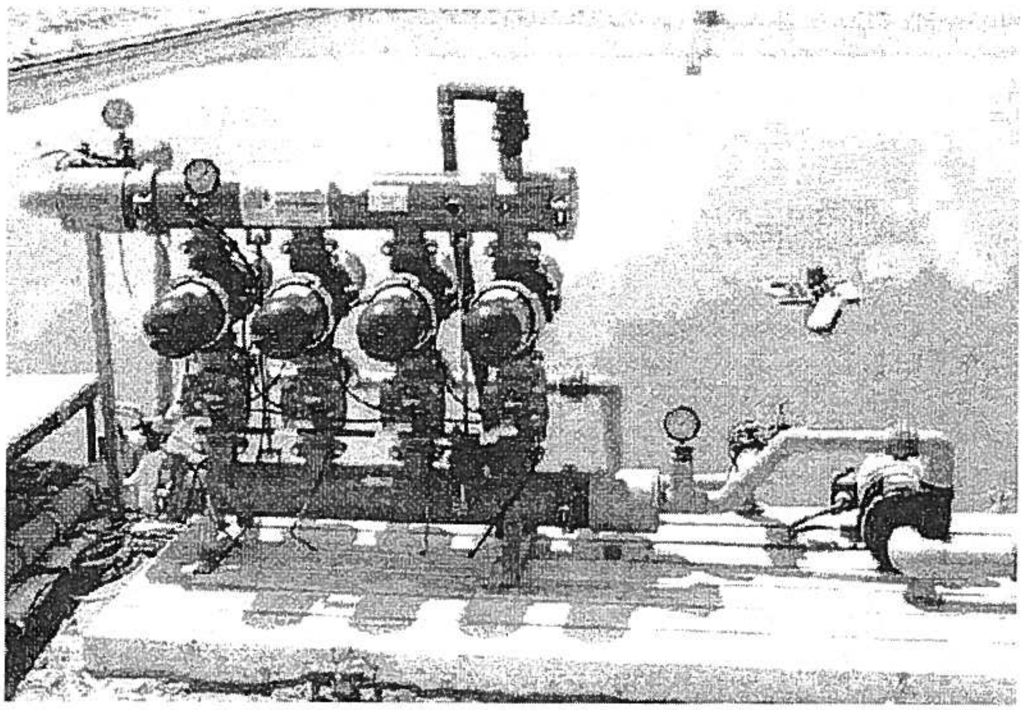

Figure 6: Disk filters

They are a hybrid of screen filters and sand media filters. Water flows in microscopic grooves between disks that filter the particles. Disk filters generally separate during back flushing and require less water than media filters. However, back flushing pressure as high as 50 psi may be required, which may require the use of a pressure-sustaining valve or booster pump or both. Separation of the disks may not be desirable if sand is present. Sand may be removed by using a sand separator before the disk filter. A typical recommended flow rate for filtering groundwater with 200-mesh-equivalent disk filters is 50 gpm per square foot of filter area. Chlorine injection is commonly used to insure that any unfiltered biological material does not accumulate elsewhere in the SDI system. If the microbiological load of the irrigation water is high, a low concentration (1 to 2 ppm) of chlorine should be injected continuously. Chlorine shock treatment may be desirable even when biological load is not particularly high, but a single biological clogging is suspected. A shock treatment uses a concentration of 10 to 30 ppm. Frequency and duration of shock treatments are determined by the severity of the problem. Considering 20 ppm injection for a 600 gpm well, one would require, 0.012 gallons of chlorine per minute. Household bleach generally contains about 2.5 percent of chlorine. So one will need to inject about half a gallon of bleach per minute. Chlorine injection rate calculation formula is provided in K-State bulletin no. MF-2361, titled *Filtration and Maintenance Considerations for Subsurface Drip Irrigation (SDI) Systems.*

Chlorine gas is the most effective and least expensive chlorine source for injection. This may be hazardous and must be used with caution. Specialized controllers are available and service providers may supply gas cylinders. Sodium hypo chlorite (liquid bleach) is safer and easy to obtain and use. It degrades over time so it should not be stored for long periods of time. Calcium hypo chlorite granules or tablets are more stable than bleach, but more expensive. Chlorine has no effect on scale deposits. There are other commercial materials to dislodge scales.

Chemical clogging hazards

Two major chemical clogging hazards to SDI systems in the Great Plains are precipitation of calcium carbonate (CaCO3 also called lime), and formation of iron ochre (slime). Precipitation of CaCO3 can occur in one of two ways: evaporation of water, leaving the salts behind, or change of solubility due to change of solution characteristics (mainly temperature or pH). Evaporation is usually not a problem in SDI systems, but chemistry changes and increased water temperature can cause CaCO3 precipitation. In SDI systems, the buried drip tapes do not get as hot as surface installed drip irrigation lines, so temperature-induced CaCO3 precipitation is not as great a problem. Increased pH also decreases CaCO3 solubility, raising the potential for precipitation. A water analysis can be used to determine the predisposition of the water source to CaCO3 precipitation. In many cases, bicarbonate may be present. Bicarbonate can react with naturally occurring calcium in the water to form calcium carbonate or lime. In many cases, if precipitation is likely to occur, acid injection is used to lower pH and decrease the propensity of CaCO3 precipitation. Lowering water pH to 6.5 cuts bicarbonate levels significantly. An acid formulation of nitrogen fertilizer (N-phuric) can be used for pH control and nitrogen fertilization concurrently. Commercial acidifiers are available in the market. Acid will also remove any existing calcium carbonate in the system. Acid is noncorrosive to pipes made of polyvinyl compound (PVC) and polyethylene (PE) tubing, but may be corrosive to steel and aluminum. At very low concentrations, it may be possible to keep iron in the solution by adding acid to lower the pH. One hazard of iron is bacterial interaction. Various bacteria can react with ferrous (+2 charge) iron through an oxidation process. The resulting ferric (+3 charge) iron is insoluble. The ferric iron eventually will be surrounded by filamentous bacteria, forming the slime or gel that clogs emitters. Chlorination is used to oxidize the ferrous iron. The resultant ferric iron is filtered before it can reach and clog the emitters. It is necessary to know the fill volume of the SDI system and determine the minimum time requirement to fill the system for a shock treatment.
Time of injection and the total volume can be calculated by knowing the flow rate, concentration of chlorine injection required, and the acreage to treat. If the water pH is high, concurrent acidification and chlorination may be required. Injection

points of the two materials into the water stream should be at least 2 to 3 feet apart. *Acid and chlorine source bleach should never be combined in the same container, because dangerous toxic chlorine gas is released.* Pump lubrication oil may cause plugging of the screen. Selecting lubrication material may help. There are some materials that may break the greasy substance produced from lubricants by soap action.

Concluding Statements

When using SDI systems, it is important to prevent clogging problems to ensure that the system will last for many years. To be economical the SDI system require to perform well for at least 15 years, which is very much possible. The best prevention plan includes an effective filtration and water treatment strategy. Depending on the water source and its quality, various combinations of sand separation, screen filtration, sand media or disk filtration, chlorination, and acid injection may be required. Filtration equipment may be the single item of greatest cost when installing the SDI system. One must resist the temptation to "cut corners." Good filtration and system maintenance will pay for itself by avoiding labor, or extra effort that may be required to fix a damaged system that was not adequately maintained. Despite all efforts on filtration, some materials will not be removed and will find their way into the drip tape. To prevent the accumulation of those materials in the drip tape and the resultant emitter clogging, the drip tapes should be flushed occasionally. A useful way to provide flushing is to connect all the distal ends of the drip tape laterals within a zone to a common sub main or flush header. This allows the flushing to be accomplished from one point, and helps in keeping the system free from accumulated sediments while providing water below the clogging point of any plugged drip tape. If a break occurs, positive water pressure on both sides will limit sediment intrusion. Flow meters and pressure gauges should be checked periodically to assure that the system is operating correctly. If measured flow rates and pressure distributions indicate problems in the system, some reconditioning may be possible with chemical injection (including chlorine shock treatments), flushing, and other steps. Profit margins for crops typically grown in the Great Plains are not as high as the profit margins for fruits and vegetables traditionally grown with SDI systems. To make SDI systems in the Great Plains economically viable— they must have a long life. Prevention of clogging is therefore critical to the successful and economical use of SDI in the Great Plains.

Reference

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Visit K-State web page on SDI at: http://www.oznet.ksu.edu/sdi
Also at: http://www.oznet.ksu.edu/library/ageng2/

SDI WATER QUALITY ASSESSMENT GUIDELINES

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K-State Research and Extension

INTRODUCTION

Water quality can have a significant effect on Subsurface Drip Irrigation (SDI) system performance and longevity. In some instances, poor water quality, such as high salinity, could cause soil quality and crop growth problems. However, with proper treatment and management, water with high mineral loading, water with nutrient enrichment or water with high salinity can be used successfully in SDI systems. However, no system should be designed and installed without first assessing the quality of the proposed irrigation water supply.

SAMPLING REQUIREMENTS

Water samples should be collected in clean triple rinsed plastic bottles. Well water samples should be collected after the well has been operating for at least 15 minutes. Surface water samples should be collected below the water surface. If the quality varies throughout the pumping season, chose the worst case sample, or sample multiple times. Generally about a half gallon of water is needed to perform the required chemical analysis. The samples need to be analyzed within 3 hours. If this is not practical, the samples can be frozen or held below 40°F. *It is advisable to check with the lab for specific collection and handling instructions for the sample.* Be certain to let them know the type of tests of interest. These tests are discussed below.

WATER QUALITY ANALYSIS RECOMMENDATIONS

Prevention of clogging is the key to SDI system longevity and prevention requires understanding of the potential problems associated with a particular water source. Information on water quality should be obtained and made available to the designer and irrigation manager in the early stages of the planning process so that suitable system components, especially the filtration system, and appropriate management and maintenance plans can be selected. Recommended water quality tests include:

1. **Electrical Conductivity (EC)**, measured in ds/m or mmho/cm. A measure of total salinity or total dissolved solids;
2. **pH**, a measure of acidity - where 1 is very acid, 14 is very alkali, and 7 is neutral;
3. **Cations** - measured in meq/L (milliequivalent/liter), includes:
   Calcium (Ca),
   Magnesium (Mg), and
   Sodium (Na);
4. **Anions** - measured in meq/L, includes:
   Chloride (Cl),
   Sulfate (SO4),
   Carbonate (CO3), and
   Bicarbonate (HCO3);
5. **Sodium Absorption Ratio (SAR)** - a measure of the potential for sodium in the water to develop sodium sodicity, deterioration in soil permeability and toxicity to crops. SAR is sometimes reported as Adjusted (Adj) SAR. The Adj. SAR value better accounts for the effect on the HCO3 concentration and salinity in the water and the subsequent potential damage by sodium to the soil.
6. **Nitrate nitrogen (NO3 - N)** - measured in mg/L (milligram/liter);
7. **Iron (Fe)**,
   Manganese (Mn), and
   Hydrogen Sulfide (H2S) - measured in mg/L;
8. **Total suspended solids (TSS)** - a measure of particles in suspension - in mg/L;
9. **Bacterial population** - a measure or count of bacterial presence in # / ml, (number per milliliter);
10. **Boron*** - measured in mg/L;
11. **Presence of oil****

* The boron test would be for crop toxicity concern.
** Oil in water would be concern for excessive filter clogging. It may not be a test option at some labs and could be considered an optional analysis.

Tests 1 through 7 are likely to be test results provided in a standard irrigation water quality test package. Tests 8 through 11 are generally offered by water labs as individual tests. The test for presence of oil may be a test to consider in oil producing areas of the state or if the well to be used for SDI has experienced surging which may have introduced oil into the pumped water. The fee schedule for tests1 through 11 will vary from lab to lab. The total cost for all recommended tests may be a few hundred dollars. This is still minor investment in comparison to the value offered by the test in helping to determine proper design and operation of the SDI system.

Water testing can be done by a number of laboratories in the state; be sure to use a certified lab. *Remember to always check with the lab in advance of collecting any sample for specific collection procedure, test kits or handling procedures needed to assure quality.* Table 1 summarizes the water quality guidelines for clogging potential. These are guidelines to help interpret water quality test results.

Most surface and groundwater supplies in the region will be fairly hard, that is they will have a large mineral content. In addition, many wells, especially older wells, may produce sand when pumping. These two clogging hazards are classified as chemical and physical hazards, respectively. A third clogging hazard is biological which could be slimes produced by growth of bacteria or algae.

Bacteria do not normally live in groundwater until a well allows the introduction of bacteria, an air exchange, and, in some cases, a source of nutrients. Bacteria can live on iron, manganese or sulfur. Their growth process produces a slime that can build up on the well screens and actually cause well yield declines. A bacteria contaminated well will introduce the bacteria into the SDI system which can result in clogging of the filtration system and dripline emitter. Chlorination of an irrigation well to kill bacteria, should be a routine practice (probably at least annually). Treat the well with a shock treatment of about 500 ppm. Details for shock chlorination of wells are discussed by Powell and Rogers, 1998 or contact your local well driller. A simple Excel template to calculate the chlorine rate for chlorination of deep wells is at
http://www.oznet.ksu.edu/sdi/Software/SDISoftware.htm

A well that has been shock chlorinated should be pumped to waste until the water clears. This water should never be sent through the SDI system since there will be large amounts of dislodged chemical and biological material from the well casing and screen.

Table 1. Water quality guidelines for microirrigation systems. Adapted from Hanson et. al., 1994 and Hassan, 1998.

Constituent	Level of Concern		
Clogging Potential	**Low**	**Moderate**	**High**
pH	< 7.0	7 - 8	> 8.0
Iron (Fe) mg/L	< 0.2	0.2 - 1.5	> 1.5
Manganese (Mn) mg/L	< 0.1	0.1 - 1.5	> 1.5
Hydrogen Sulfide (H_2S) mg/L	< 0.2	0.2 - 2.0	> 2.0
Total Dissolved Solids (TDS) mg/l	< 500	500 - 2000	> 2000
Total Suspended Solids (TSS) mg/L	< 50	50 - 100	> 100
Bacteria Count (# / mL)	< 10,000	10,000 - 50,000	> 50,000
Crop Effects	**Low**	**Moderate**	**High**
EC - mmho/cm	< 0.75	0.75 - 3.0	> 3.0
NO_3 - mg/L	< 5	5 - 30	> 30
Specific Ion Toxicity	**Low**	**Moderate**	**High**
Boron - mg/L	< 0.7	0.7 - 3.0	> 3.0
Chloride - meq/L	< 4	4 - 10	> 10.0
Chloride - mg/L	< 142	142 - 355	> 355
Sodium (Adj SAR)	< 3.0	3 - 9	> 9

Chlorination of the SDI system is also a practice that should be a routine maintenance procedure, since chlorine will oxidize biological material. Bacterial growth in driplines can be additionally troublesome due to small clay particles in the water that are smaller than the required level of filtration. The sticky slime growth may cause these small particles to stick together with the resultant effect of clogging emitters.

Chlorine can be injected to kill bacteria either continuously with a low dosage base (0.5-1.5 ppm) or periodically at a high dose of 5 to 20 ppm. Periodic dosage is most common in Kansas systems. The dosage level should be sufficient that a concentration of 0.5 to 1 ppm of free chlorine should be measured at the end of the system. Chlorine is more effective in acid waters. High pH or alkaline waters should be acidified to a pH of 6.5 for effective chlorine treatment. Acid treatment can also an effective treatment for bacteria growth.

The general formula for calculating the amount of chlorine to inject in liquid form (sodium hypochlorite, NaOC) is:

$$\mathbf{IR = Q \times C \times 0.006/S}$$

where
IR = Chlorine injection rate (gal/hour)
Q = Irrigation system flow rate (gal/min)
C = Desired chlorine concentration (ppm)
S = Strength of NaOC solution used (percent)

Example: *A grower wishes to use household bleach (NaOC at 5.25 percent active chlorine) to achieve a 15 ppm chlorine level at the injection point. The flow rate of the irrigation systems is 700 gpm. At what rate should the NaOC be injected?*

IR = 700 gpm x 15 ppm x 0.006 / 5.25
= 12 gallon per hour

At an irrigation flow rate of 700 gpm, the grower is pumping (700 x 60) 42000 gph (i.e. 700 x 60). The goal is to inject 12 gallons of bleach into 42000 gallons of water each hour that injection occurs.

If the injector is set for a 500:1 ratio, it will inject 42000/500 or 84 gallons per hour. Then, 12 gallons of bleach should be added to 72 gallons of water to make the 84 gallons of stock solution. Note: be careful to use the same time units (hours) when calculating the injection rate.

Common household bleach is generally a 5.25 to 7.5 percent solution. Stronger concentrations of chlorine solutions are available from irrigation dealers and industrial suppliers.

The injected chlorine must travel through the entire system during the injection period. The propagation time should be calculated or obtained from the installer. Alternatively, water from the flushline can be tested to see if a free chlorine residual is detected. This would indicate a sufficient injection time has elapsed.

CHEMICAL PRECIPITATION

Chemical precipitation hazard guidelines, as shown in Table 1, give some indication of potential clogging hazard. SDI systems have an advantage over surface drip systems in that the driplines are below ground and buffered from sunlight and temperature that could help drive both biological and chemical activity. Water pH and temperature also plays a major role in many reactions.

In addition to the discussion to follow, several references also noted groundwater test interpretations and are summarized in Table 2.

Table 2. Notes on Chemical Clogging Hazards

Bicarbonate concentrations exceeding about 2 meg/L and pH exceeding about 7.5 can cause calcium carbonate precipitation.
Calcium concentrations exceeding 2 to 3 meg/L can cause precipitates to form during injection of some phosphate fertilizers. Special procedures are necessary for the injection of phosphate fertilizers and injection should be only attempted by experienced personnel using care.
High concentrations of sulfide ions can cause iron and manganese precipitation. Iron and manganese sulfides are very insoluble, even in acid solutions. In this case, frequent acidification or the use of a settling basin for separating iron and manganese precipitants is advisable.
Irrigation water containing more than 0.1 ppm sulfides may encourage growth of sulfur bacteria within the irrigation system. Regular chlorination may be needed.
Chlorination when manganese is present should be used with caution as a reaction time delay may occur between chlorination and the development of the precipitate. This may cause the manganese precipitate to form downstream of the filter and cause emitter clogging.

CALCIUM CARBONATE

Calcium carbonate, commonly known as lime, can be a problem with high pH (>7.5) and high bicarbonate levels (> 2meg/L). The symptoms of calcium precipitation is a white film or plating on the dripline or around the emitters or white precipitants in the flush water of the driplines.

The usual treatment for calcium precipitation is to acidify the water by lowering the pH to 7.0 or lower with continuous injection. Calcium becomes more soluble at low pH. When using a periodic injection treatment, pH may have to be lowered to 4.0 or less and allowed to sit in the system for up to 60 minutes.

Temperature, pH and the calcium concentration all affect calcium solubility, so conditions will vary throughout the system. Litmus paper, colormetric kits, or a portable pH meter can be used to measure the pH at the lower end of the system to determine if free chlorine exists.

Sulfuric acid or hydrochloric acid can be used to reduce pH. Muriatic acid (20% hydrochloric acid) may be the most commonly available acid from hardware or farm supply stores. Urea sulfuric acid, an acid with nitrogen fertilizer value, can also be used. This product is safer to use and is marketed as N-pHuric *. Check with your irrigation dealer or your fertilizer dealer about its availability in your region. **Caution: Use extreme care in handling acids and always add acid to water.** Be certain to flush and clean the injection system after an acid treatment as the acid may be corrosive to internal parts. Remember also, treatments need to be done before total blockage of emitters occur. Remediation, after total blockage, is difficult or impossible since the acid will not come into contact with the precipitants in passages closed to water movement.

IRON AND MANGANESE

Iron and manganese precipitation can become a problem with concentrations as low as 0.1 ppm. Most groundwater contains some iron and manganese but in a soluble state but when exposed to air, they oxidize and precipitate as a solid. Irrigators with center pivots, especially center pivots using alluvial groundwater supplies, often see the structures turn red in very short usage times. These compounds can also be used as an energy source by bacteria. They form the filamentous slime, discussed previously, that can clog filters and emitters and act as a glue to adhere other contaminants together.

Symptoms of iron precipitation would be reddish stain and rust particles in the flush water and reddish deposits in the orifices. Manganese would be similar but darker color or black. Bacterial slimes would be of similar color as precipitants but appear as filamentous sludge in the flush water or collected on the screens.

AERATION AND SETTLING

One effective option for removal of high concentrations of iron and manganese for high flow rate systems is the use aeration and settling basins, especially for manganese. The oxidation rate of manganese is much slower than for iron, making manganese problematic for removal with some of the other treatment methods.

Aeration of the source water occurs by spraying water into the air or running it over a series of baffles to enhance the mixing of oxygen into the water. There must be sufficient aeration and reaction time; the soluble forms of manganese and iron will oxidize and precipitate. The disadvantage of this treatment is the need for a second pump. Total head requirements are not changed when using two pumps, so energy costs are not a major factor. Additionally, a settling basin requires a site, will entail construction costs, and have long term maintenance requirements. Algae and bacteria control in the basin by chlorination may be required.

CHLORINATION AND FILTRATION

Injection of chlorine into water will cause the dissolved iron to precipitate, so it can then be filtered out. The reaction occurs quickly but injections need to be located well upstream of the filter. This treatment method may be best suited for systems with sand media filters. Chlorine is injected at a rate of 1 ppm for each 0.7 ppm of iron. Additional chlorine may be required if other contaminates, such as iron bacteria, are also present. This treatment requires continuous injection of chlorine. Successful treatment also requires complete mixing of the chorine in the water.

This treatment method is not suited to manganese removal because of its slower oxidation rate. If manganese and free chlorine remain in the line after filtration, precipitation may then occur which could clog emitters.

pH CONTROL

Iron is more soluble at lower ph, therefore acid can be used on a continuous or periodic treatment basis as described for calcium carbonate. In this case, the pH should be lowered to 2.0 or less for 30 to 60 minutes for a periodic or cleaning treatment. After a periodic treatment, the system must be flushed.

IRON AND MANGANESE SULFIDES

Dissolved iron and manganese, in the presence of sulfides, can form a black sand-like insoluble precipitant. The recommended treatment for this combination of compounds would be continuous acid injection that lowers pH to between 5 and 7.

Sulfur slime can also be produced by bacteria that can oxidize hydrogen sulfide and produce elemental sulfur. The systems of this condition are white cottony masses of slime which either clog emitters directly or again act as glue to collect small silt and clay particles that clump together and then clog emitters.

TREATMENT SUMMARY

The symptoms and treatments for the various clogging hazards are summarized in Table 3.

Table 3. Water treatments to prevent clogging in microirrigation systems. Adapted from Hanson et. al, 1994

Problem	Treatment Options
Carbonate precipitation (white precipitate) *Hazard level:* HCO_3 greater than 2.0 meq/l pH greater than 7.5	1. Continuous injection: maintain pH between 5 and 7 2. Periodic injection: maintain pH at under 4 for 30-60 minutes daily
Iron precipitation (reddish precipitate) *Hazard level:* Iron concentrations greater than 0.1 ppm	1. Aeration and settling to oxidize iron. (Best treatment for high concentrations-10 ppm or more). 2. Chlorine precipitation - injecting chlorine to precipitate iron: a. use an injection rate of 1 ppm of chlorine per 0.7 ppm of iron b. inject in front of the filter so that the precipitate is filtered out 3. Reduce pH to 4 or less for 30-60 minutes daily.
Manganese precipitation (black precipitate) *Hazard level:* Manganese concentrations greater than 0.1 ppm	1. Inject 1 ppm of chlorine per 1.3 ppm of manganese in front of the filter
Iron bacteria (reddish slime) *Hazard level:* Iron concentrations greater than 0.1 ppm	1. Inject chlorine at a rate of 1 ppm free chlorine continuously or 10 to 20 ppm for 30 to 60 minutes daily.
Sulfur bacteria (white cottony slime) *Hazard level:* Sulfide concentrations greater than 0.1 ppm	1. Inject chlorine continuously at a rate of 1 ppm per 4 to 8 ppm of hydrogen sulfide, or 2. Inject chlorine intermittently at 1 ppm free chlorine for 30 to 60 minutes daily.
Bacterial slime, Algae	1. Inject chlorine at a rate of 0.5 to 1 ppm continuously or 20 ppm for 20 minutes at the end of each irrigation cycle.
Iron sulfide (black sand-like material) *Hazard level:* Iron and sulfide concentrations greater than 0.1 ppm	1. Dissolve iron by injecting acid continuously to lower pH to between 5 and 7.

SUMMARY

Subsurface drip irrigation offers a number of agronomic production and water conservation advantages but requires proper design, operation, and maintenance to be an efficient, effective and long-lived irrigation system. One management change from the current irrigation systems is the need to understand the SDI system sensitivity to clogging by physical, biological or chemical agents.

Before designing or installing an SDI system, be certain a comprehensive water quality test is conducted on the source water supply. Once this assessment is complete, the manager can then be made aware of any potential problems that might be caused by the water supply. The old adage "an ounce of prevention is worth a pound of cure" is very appropriate for SDI systems as early recognition of developing problems can head off many problems if appropriate action is taken. Developing problems can be easily handled as compared to remediation of a clogged system. While this may seem daunting at first, as with most new technology, most managers will quickly become familiar with the system and its operational needs.

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KSU RESEARCH FOR CORN PRODUCTION USING SDI: 14 YEARS OF PROGRESS

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BRIEF HISTORY

In the summer of 1988, K-State Research and Extension issued an in-house request for proposals for new directions in research activity. A proposal entitled Sustaining Irrigated Agriculture in Kansas with Drip Irrigation was submitted by irrigation engineers Freddie Lamm, Harry Manges and Dan Rogers and agricultural economist Mark Nelson. This project led by principal investigator Freddie Lamm, Northwest Research-Extension Center (NWREC), Colby, was funded for the total sum of $89,260. This project financed the initial development of the NWREC SDI system that was expressly designed for research. In March of 1989, the first driplines were installed on a 3 acre study site which has 23 separately controlled plots. This site has been in continuous use in SDI corn production since that time, being initially used for a 3-year study of SDI water requirements for corn. In addition, it is considered to be a benchmark area that is also being monitored annually for system performance to determine SDI longevity. In the summer of 1989, an additional 3 acres was developed to determine the optimum dripline spacing for corn production. A small dripline spacing study site was also developed at the Southwest Research-Extension Center (SWREC) at Garden City in the spring of 1989.

In the summer of 1989, further funding was obtained through a special grant from the US Department of Agriculture (USDA). This funding led to expansion of the NWREC SDI research site to a total of 13 acres and 121 different research plots. This same funding provided for the 10 acre SDI research site at Holcomb, Kansas administered by the SWREC. By June of 1990, K-State Research and Extension had established 25 acres of SDI research facilities and nearly 220 separately controlled plot areas.

Over the course of the past 14 years, additional significant funding has been obtained to conduct SDI research from the USDA, the Kansas Water Resources Research Institute, special funding from the Kansas legislature, the Kansas Corn

Commission, Pioneer Hi-Bred Inc., and the Mazzei Injector Corporation. Funding provided by the Kansas legislature through the Western Kansas Irrigation Research Project (WKIRP) allowed for the expansion of the NWREC site by an additional 5.5 acres and 46 additional research plots in 1999. The NWREC SDI research site comprising 18.5 acres and 167 different research plots is the largest facility devoted expressly to small-plot row crop research in the Great Plains and is probably one of the largest such facilities in the world.

Since its beginning in 1989, K-State SDI research has had three purposes: 1) to enhance water conservation; 2) to protect water quality, and 3) to develop appropriate SDI technologies for Great Plains conditions.

The vast majority of the research studies have been conducted with field corn because it is the primary irrigated crop in the Central Great Plains. Although field corn has a relatively high water use efficiency, it generally requires a large amount of irrigation because of its long growing season and its sensitivity to water stress over a great portion of the growing period. Of the typical commodity-type field crops grown in the Central Great Plains, only alfalfa and similar forages would require more irrigation than field corn. Any significant effort to reduce the overdraft of the Ogallala aquifer, the primary water source in the Central Great Plains, must address the issue of irrigation water use by field corn.

GENERAL STUDY PROCEDURES

This report summarizes several studies conducted at the KSU Northwest and Southwest Research-Extension Centers at Colby and Garden City, Kansas, respectively. A complete discussion of all the employed procedures lies beyond the scope of this paper. For further information about the procedures for a particular study the reader is referred to the accompanying reference papers when so listed. The following general procedures apply to all studies unless otherwise stated.

The two study sites were located on deep, well-drained, loessial silt loam soils. These medium-textured soils, typical of many western Kansas soils, hold approximately 18.9 inches of plant available soil water in the 8 ft profile at field capacity. Study areas were nearly level with land slope less than 0.5% at Colby and 0.15% at Garden City. The climate is semi-arid, with an average annual precipitation of 18 inches. Daily climatic data used in the studies were obtained from weather stations operated at each of the Centers.

The studies utilized SDI systems installed in 1989-90 (Lamm et al., 1990). The systems have dual-chamber drip tape installed at a depth of approximately 16-18 inches with a 5 ft spacing between dripline laterals. Emitter spacing was 12 inches and the dripline flowrate was 0.25 gpm/100 ft. The corn was planted so each dripline lateral is centered between two corn rows (Figure 1).

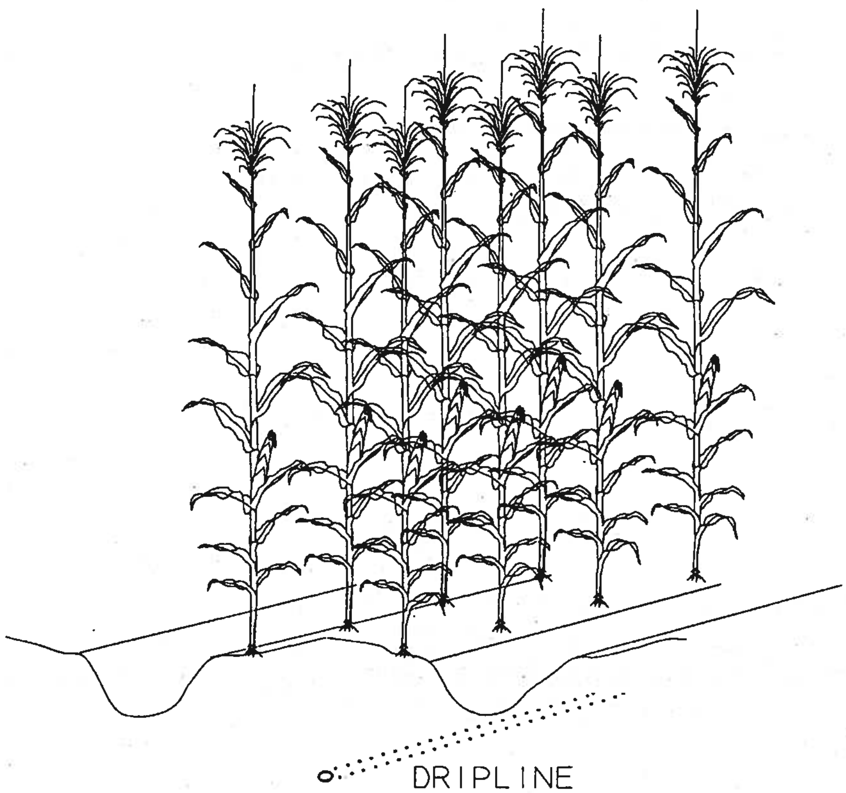

Figure 1. Physical arrangement of the subsurface dripline in relation to the corn rows.

A modified ridge-till system was used in corn production with two corn rows, 30 inches apart, grown on a 5 ft wide bed. Flat planting was used for the dripline spacing studies conducted at both locations. In these studies, it was not practical to match bed spacing to dripline spacing with the available tillage and harvesting equipment. Additionally at Garden City, corn rows were planted perpendicular to the driplines in the dripline spacing study. All corn was grown with conventional production practices for each location. Wheel traffic was confined to the furrows.

Reference evapotranspiration and actual evapotranspiration (AET) was calculated using a modified Penman combination equation similar to the procedures outlined by Kincaid and Heerman (1974). The specifics of the calculations are fully described by Lamm et al. (1995).

Irrigation was scheduled using a water budget to calculate the root zone depletion with precipitation and irrigation water amounts as deposits and calculated daily corn water use (AET) as a withdrawal. If the root-zone depletion became negative, it was reset to zero. Root zone depletion was assumed to be zero at crop emergence. Irrigation was metered separately onto each plot. Soil water amounts were monitored weekly in each plot with a neutron probe in 12 inch increments to a depth of 8 ft.

WATER REQUIREMENT AND IRRIGATION CAPACITY STUDIES

Research studies were conducted at Colby and Garden City, Kansas from 1989-1991 to determine the water requirement of subsurface drip-irrigated corn. Careful management of SDI systems reduced net irrigation needs by nearly 25%, while still maintaining top yields of 200 bu/a (Lamm et. al., 1995). The 25% reduction in irrigation needs potentially translates into 35-55% savings when compared to sprinkler and furrow irrigation systems which typically are operating at 85 and 65% application efficiency. Corn yields at Colby were linearly related to calculated crop water use (Figure 2), producing 19.6 bu/a of grain for each mm of water used above a threshold of 12.9 inches (Lamm et al., 1995). The relationship between corn yields and irrigation is nonlinear (Figure 2.) primarily because of greater drainage for the heavier irrigation amounts (Figure 3).

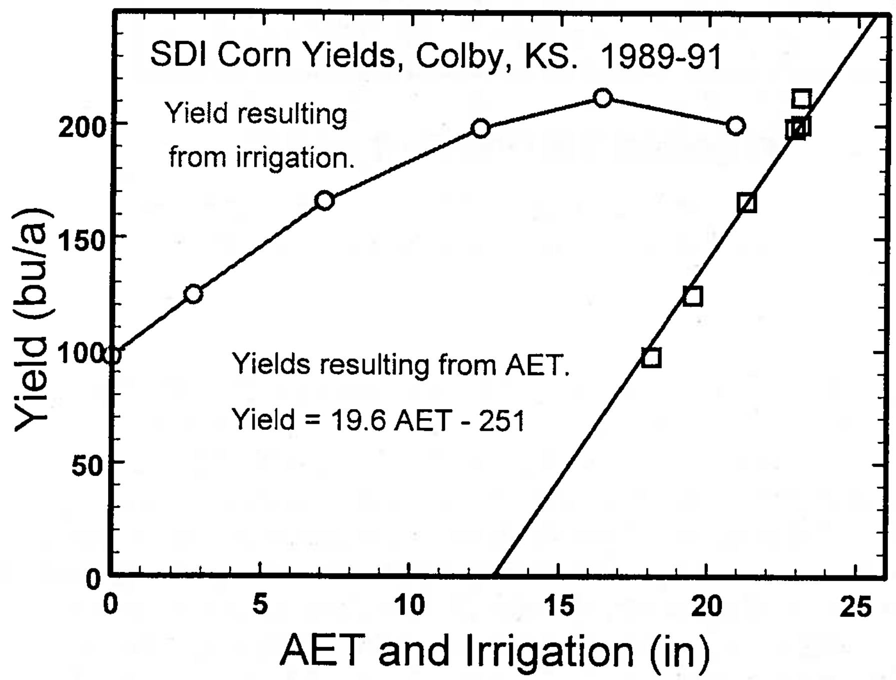

Figure 2. Corn yield as related to irrigation and calculated evapotranspiration (AET) in a SDI water requirement study, Colby, KS., 1989-1991.

SDI technology can make significant improvements in water use efficiency through better management of the water balance components. The 25% reduction in net irrigation needs is primarily associated with the reduction in in-season drainage, elimination of irrigation runoff and reduction in soil evaporation, all non-beneficial components of the water balance. Additionally, drier surface soils allow for increased infiltration of occasional precipitation events.

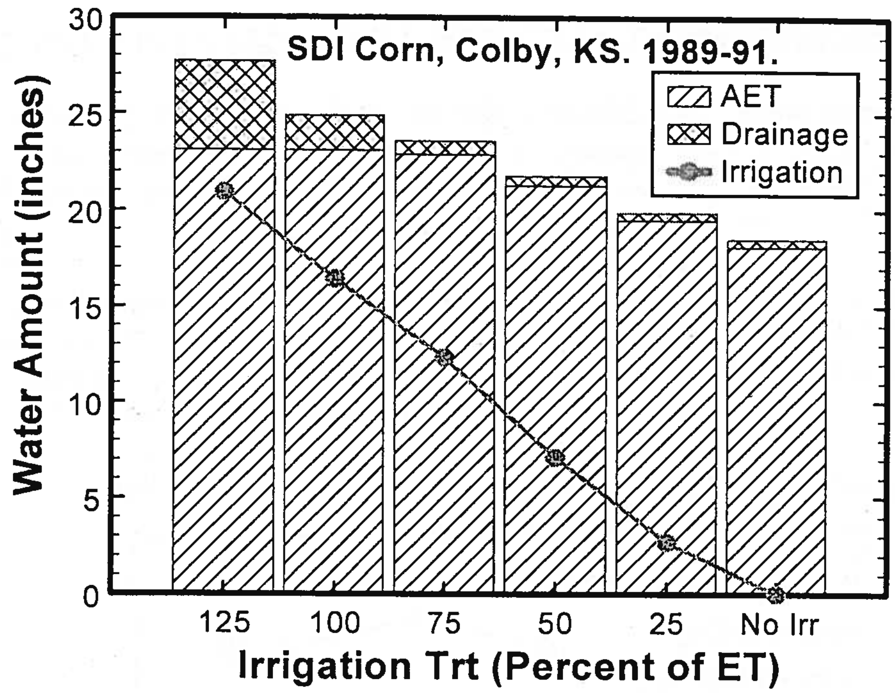

Figure 3. Calculated evapotranspiration (AET) and seasonal drainage as related to irrigation treatment in a SDI water requirement study, Colby, KS., 1989-1991.

In a later study (1996-2001), corn was grown with subsurface drip irrigation (SDI) under 6 different irrigation capacities (0, 0.10, 0.13, 0.17, 0.20 and 0.25 inches/day) and 4 different plant populations (33100, 29900, 26800, and 23700 plants/acre). All treatments were irrigated during the offseason to recharge the soil water profile. The purpose of the study was to determine appropriate inseason SDI capacities as related to different corn plant populations. Daily SDI application of even small amounts of water (0.10 inches) doubled corn grain yields from 93 to 202 in extremely dry 2000 and 2001 (Figure 4). Results suggested an irrigation capacity of 0.17 inches/day might be adequate SDI capacity when planning new systems in this region on deep silt loam soils (Lamm and Trooien, 2001). Analysis of the yield component data indicated that the number of kernels/acre is largely determined by providing just a small amount of SDI capacity over the nonirrigated control. It was concluded that small daily amounts of water can be beneficial on these deep silt loam soils in establishing the number of sinks (kernels) for the accumulation of grain. The final kernel weight is established by grain filling conditions between the reproductive period and physiological maturity (last 50-60 days of crop season). Thus the extent of mining of the soil water reserves during this period will have a large effect on final kernel weight and ultimately, corn grain yield. Increasing plant population from approximately 22,500 to 34,500 plants/acre generally increased corn grain yields for SDI in this region, particularly in good corn production years. There was very little yield penalty for increased plant population even when irrigation was severely limited or eliminated.

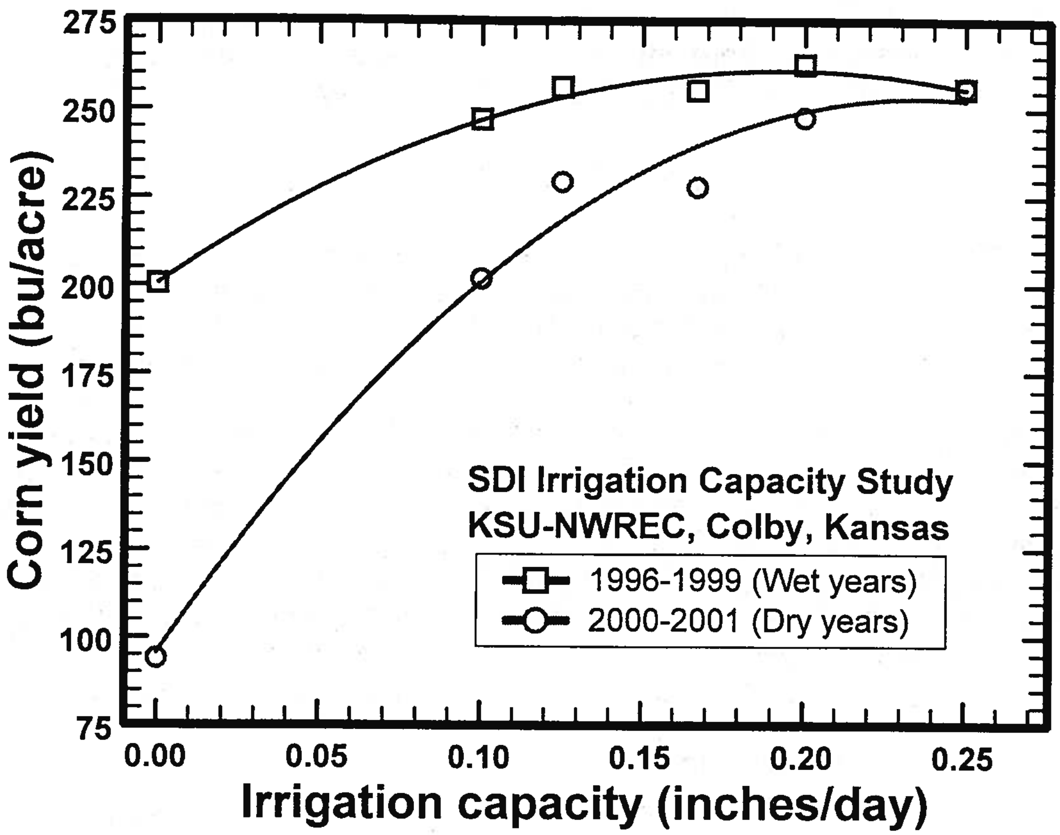

Figure 4. SDI corn grain yields as affected by irrigation capacity for wet (1996-1999) and dry years (2000-2001), KSU Northwest Research Extension Center, Colby, Kansas.

SDI FREQUENCY

Typically, a smaller volume of soil is wetted with SDI as compared to other types of irrigation systems and as a result, crop rooting may be limited. Crops may benefit from frequent irrigation under this condition. However, in a study conducted at the KSU Southwest Research-Extension Center in Garden City, Kansas, corn yields were excellent (190 to 200 bu/a) regardless of whether a frequency of 1, 3, 5, or 7 days was used for the SDI events (Caldwell et al., 1994). Higher irrigation water use efficiencies were obtained with the longer 7-day frequency because of improved storage of in-season precipitation and because of reduced drainage below the rootzone. The results indicate there is little need to perform frequent SDI events for fully-irrigated corn on the deep silt loam soils of western Kansas. These results agree with a literature review of SDI (Camp, 1998) that indicated that SDI frequency is often only critical for shallow rooted crops on shallow or sandy soils. An additional study conducted in the U.S. Southern Great Plains indicated that longer irrigation frequencies had no effect on corn yields provided soil water was managed within acceptable stress ranges (Howell et al., 1997). There is some evidence that daily irrigation events may be beneficial under deficit irrigation conditions or in cases where fertigation is practiced. Several of the more advanced research studies currently underway at Kansas State University routinely utilize daily irrigation events.

OPTIMAL DRIPLINE SPACING

Increasing the spacing of dripline laterals would be one of the most important factors in reducing the high investment costs of SDI. Soil type, dripline installation depth, crop type and the reliability and amount of in-season precipitation are major factors that determine the maximum dripline spacing.

Two studies have been conducted in semi-arid western Kansas to determine the optimum dripline spacing (installed at a depth of 16-18 inches) for corn production on deep, silt-loam soils (Lamm et al., 1997a, Manges et al., 1995). The first study at the KSU Southwest Research-Extension Center at Garden City, Kansas evaluated 4 spacings (2.5, 5, 7.5, and 10 ft) with corn planted in 30 inches rows perpendicular to the dripline lateral. The other study at the KSU Northwest Research-Extension Center at Colby, Kansas evaluated 3 spacings (5, 7.5, and 10 ft) with corn planted in 30 inch rows parallel to the driplines. Average yields for corresponding treatments were similar between sites even though row orientation was different (Table 1).

Table 1. Corn yields obtained with various dripline spacing treatments under full and reduced irrigation at Garden City and Colby, Kansas, 1989-91.

Spacing treatment	Irrigation treatment	Dripline ratio in relation to 5 ft. trt.	Corn yield (bu/a) Garden City 1989-91	Colby 1990-91
2.5 ft.	Full irrigation	2.00	230	----
5.0 ft	Full irrigation	1.00	218	216
7.5 ft	Full Irrigation	0.67	208	204
7.5 ft	Reduced irrigation (67%)	0.37	----	173
10.0 ft	Full irrigation	0.50	194	194
10.0 ft	Reduced irrigation (50%)	0.50	----	149

The highest average yield was obtained by the 2.5 ft dripline spacing at Garden City, Kansas. However, the requirement of twice as much dripline (dripline ratio, 2.00) would be uneconomical for corn production as compared to the standard 5 ft. dripline spacing. The results, when incorporated into an economic model, showed an advantage for the wider dripline spacings (7.5 and 10 ft.) in some higher rainfall years. However, the standard 5 ft dripline spacing was best when averaged over all years for both sites. When subsurface driplines are centered between alternate pairs of 30-inch spaced corn rows, each corn row is within 15 inches of the nearest dripline (Figure 1.)

Wider dripline spacings will not consistently (year-to-year) or uniformly (row-to-row) supply crop water needs. In 1990 at Colby, yields for the 5 and 7.5 ft dripline spacings were equal when full irrigation was applied, partially because soil water reserves were high at planting. In 1991, following a dry winter, yields for the wider 7.5 ft dripline spacing were reduced by 25 bu/a (Lamm et al., 1997a). Similar results were reported by Spurgeon et al. (1991) at Garden City. The studies at Colby also sought to resolve whether equivalent amounts of water should be applied to the wider dripline spacings or whether irrigation should be reduced in relation to the dripline ratio. Yields were always lower for the corn rows furthest from the dripline in the wider dripline spacings regardless of which irrigation scheme was used (Figure 5). However in 1991, there was complete crop failure in the corn rows furthest from the dripline when irrigation was reduced in relation to the dripline ratio. Full irrigation on the wider dripline spacings at Colby resulted in excessive deep percolation (Darusman et al., 1997) and reduced overall water use efficiency (Lamm et al., 1997a). Soils having a restrictive clay layer below the dripline installation depth might allow a wider spacing without affecting crop yield. Wider spacings may also be allowable in areas of increased precipitation as the dependency of the crop on irrigation is decreased (Powell and Wright, 1993).

One of the inherent advantages of a SDI system is the ability to irrigate only a fraction of the crop root zone. Careful attention to proper dripline spacing is, therefore, a key factor in conserving water and protecting water quality. These research studies at Colby and Garden City, Kansas determined that driplines spaced 60 inches apart are most economical for corn grown in rows spaced 30 inches apart at least on the deep silt loam soils of the region. However, different soil types, such as sands, or different crops with less extensive root systems might require closer dripline spacing.

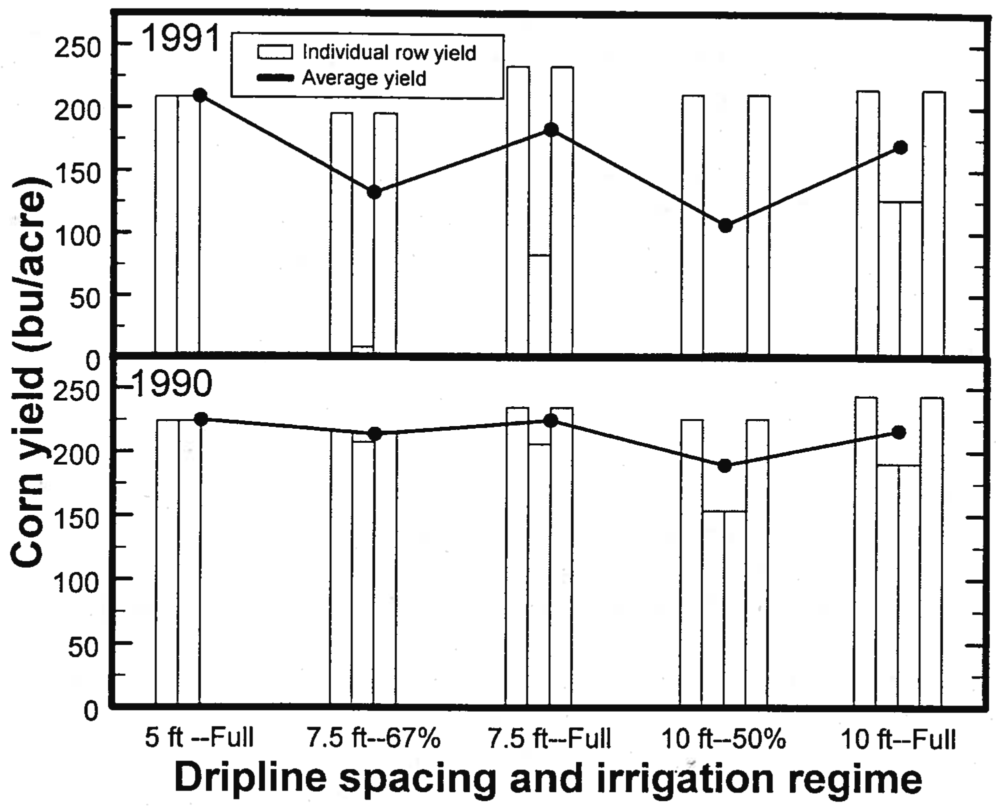

Figure 5. Corn yield distribution as affected by dripline spacing and irrigation regime, KSU Northwest Research-Extension Center, Colby, Kansas, 1990-1991. Note: Individual row yields are mirrored about a centerline half way between two adjacent driplines for display purposes.

DRIPLINE DEPTH STUDY

Subsurface drip irrigation (SDI) technologies have been a part of irrigated agriculture since the 1960s, but have advanced at a more rapid pace during the last 20 years (Camp et al. 2000). In some areas, SDI has not been readily accepted because of problems with root intrusion, emitter clogging and lack of visual indicators of the wetting pattern. In high value crops, these indeed can be valid reasons to avoid SDI. However, in the Central Great Plains, with typically relatively low value commodity crops such as corn, only long term SDI systems where installation and investment costs can be amortized over many years, have any realistic chance of being economically justified. Kansas irrigators are beginning to try SDI on their own and there has been a lack of research-based information on appropriate depth for driplines. Camp (1998) reviewed a number of SDI studies concerning depth of installation and concluded the results are often region specific and optimized for a particular crop.

A study was initiated at the KSU Northwest Research-Extension Center at Colby, Kansas in 1999 to evaluate the effect of dripline depth on corn production and SDI system integrity and longevity. The effects of five dripline depths (8, 12, 16, 20 and 24 inches) on SDI system longevity and corn production will be determined. System longevity will be evaluated by monitoring individual flowrates and pressures at the end of each cropping season to estimate system degradation (clogging) with time. There was no appreciable or consistent effect on corn grain yields during the period 1999-2002 (Figure 6.). However, it is still too early to answer questions about how depth affects longevity (chemical and biological clogging, pests, and tillage practices). The study area has not been used to examine the effects of dripline depth on germination in the spring, but studies in this regard may be conducted in the future. Damp surface soils are sometimes observed for the 8 and 12 inch dripline depths during the irrigation season, but not for the deeper depths. There is a tendency to have slightly more late season grasses for the shallower 8 and 12 inch depths, but the level of grass competition with the corn is not great. The dripline depth study is managed with the modified ridge-till system (5 ft. bed) as shown in Figure 1. Cultivation for weeds in early summer has been routinely practiced and there have been no instances thus far of tillage tool damage to the shallow 8-inch depth driplines.

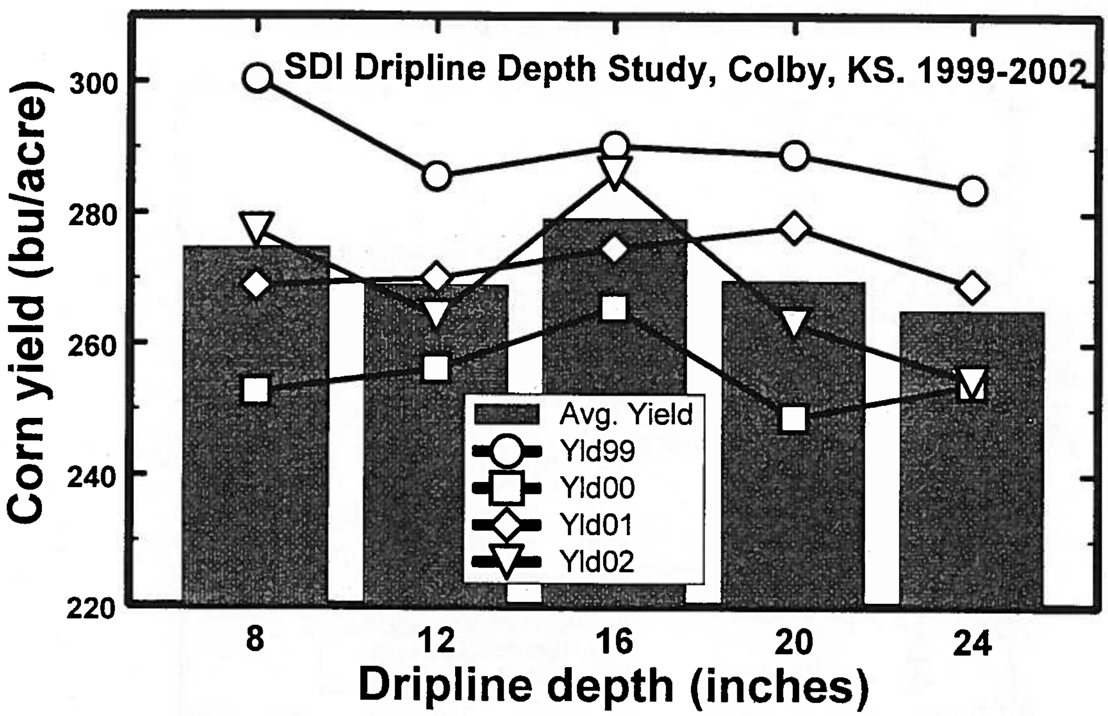

Figure 6. Corn grain yields as affected by dripline depth, 1999-2002, KSU Northwest Research-Extension Center, Colby, Kansas.

NITROGEN FERTILIZATION WITH SDI

Since properly designed SDI systems have a high degree of uniformity and can apply small frequent irrigation amounts, excellent opportunities exist to better manage nitrogen fertilization with these systems. Injecting small amounts of nitrogen solution into the irrigation water can spoonfeed the crop, while minimizing the pool of nitrogen in the soil that could be available for percolation into the groundwater.

In a study conducted at Colby, Kansas from 1990-91, there was no difference in corn yields between preplant surface-applied nitrogen and nitrogen injected into the driplines throughout the season. Corn yields averaged 225 to 250 bu/a for the fully irrigated and fertilized treatments. In both years, nearly all of the residual nitrate nitrogen measured after corn harvest was located in the upper 12 inches of the soil profile for the preplant surface-applied nitrogen treatments, regardless of irrigation level. In contrast, nitrate concentrations increased with increasing levels of nitrogen injected with SDI and migrated deeper in the soil profile with increased irrigation (Lamm et. al., 2001). Nitrogen applied with SDI at a depth of 16-18 inches redistributed differently in the soil profile than surface-applied preplant nitrogen banded in the furrow (Figure 7). *Since residual soil-nitrogen levels were higher where nitrogen was injected using SDI, it may be possible to obtain similar high corn yields using lower amounts of injected nitrogen.*

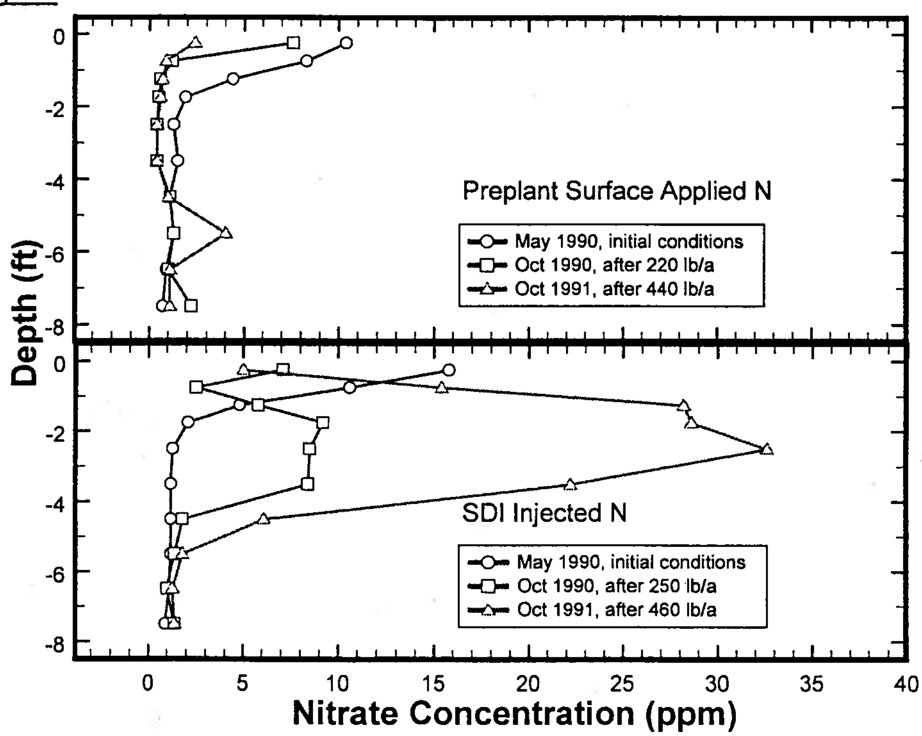

Figure 7. Nitrate concentrations in the soil profile for preplant surface-applied and SDI injected nitrogen treatments, Colby, Kansas, 1990-91. Data is for selected nitrogen fertilizer rate treatments with full irrigation (100% of AET).

A follow-up four year study was conducted at the KSU Northwest Research-Extension Center at Colby, Kansas on a deep Keith silt loam soil to develop a Best Management Practice (BMP) for nitrogen fertigation for corn using SDI. Residual ammonium- and nitrate-nitrogen levels in the soil profile, corn yields, apparent nitrogen uptake (ANU) and water use efficiency (WUE) were utilized as criteria for evaluating six different nitrogen fertigation rates, 0, 80, 120, 160, 200, and 240 lbs/acre. The final BMP was a nitrogen fertigation level of 160 lbs/acre with other non-fertigation applications bringing the total applied nitrogen to approximately 190 lbs/acre (Lamm et. al., 1997b). The BMP also states that irrigation is to be scheduled and limited to replace approximately 75% of ET. Corn yield, ANU, and WUE all plateaued at the same level of total applied nitrogen which corresponded to the 160 lbs/acre nitrogen fertigation rate (Figure 8). Average yields for the 160 lbs/acre nitrogen fertigation rate was 213 bu/acre. Corn yield to ANU ratio for the 160 lbs/acre nitrogen fertigation rate was a high 53:1. The results emphasize that high-yielding corn production also can be efficient in nutrient and water use.

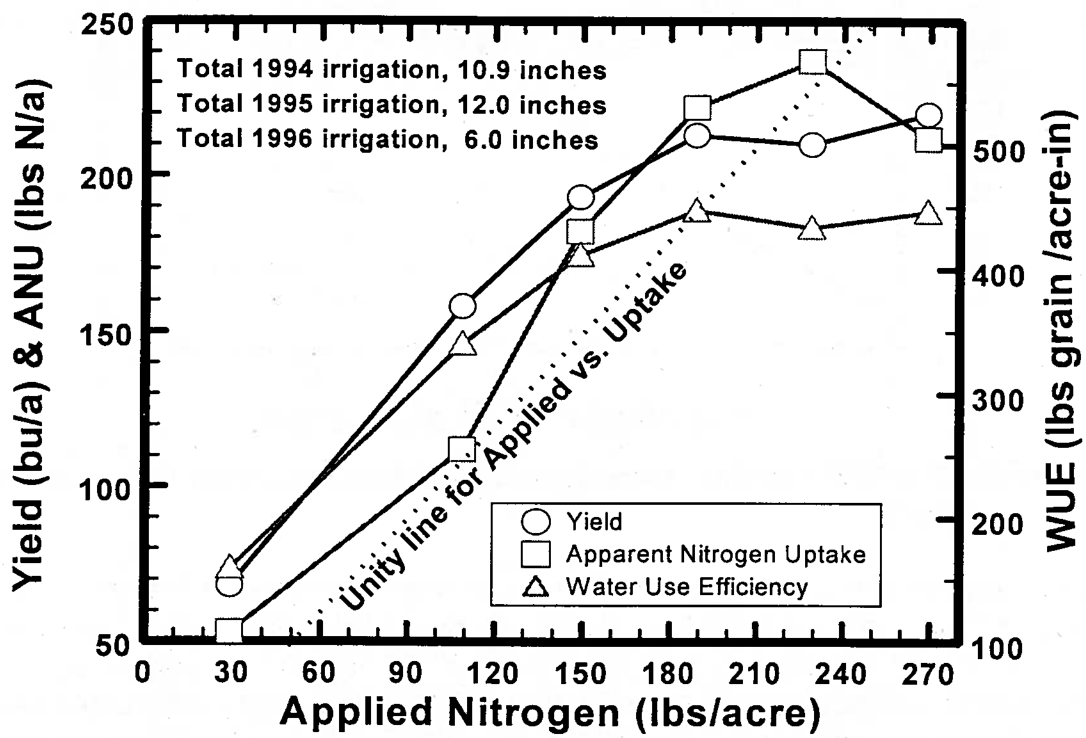

Figure 8. Average (1994-96) corn yield, apparent nitrogen uptake in the above-ground biomass, and water use efficiency as related to the total applied nitrogen (preseason amount, starter fertilizer, fertigation, and the naturally occurring N in the irrigation water). Total applied nitrogen exceeded fertigation applied nitrogen by 30 lb/acre.

ECONOMICS OF SDI

SDI has not been typically used for row crop production in the Central Great Plains. Typically, SDI has much higher investment costs as compared to other pressurized irrigation systems such as full size center pivot sprinklers. However, there are realistic scenarios where SDI can directly compete with center pivot sprinklers for corn production in the Central Great Plains. As field size decreases, SDI can more directly compete with center pivot sprinklers because of increasing higher ratio of center pivot sprinkler (CP) costs to irrigated acres (Figure 9). Small and irregular shape fields may be ideal candidates for SDI.

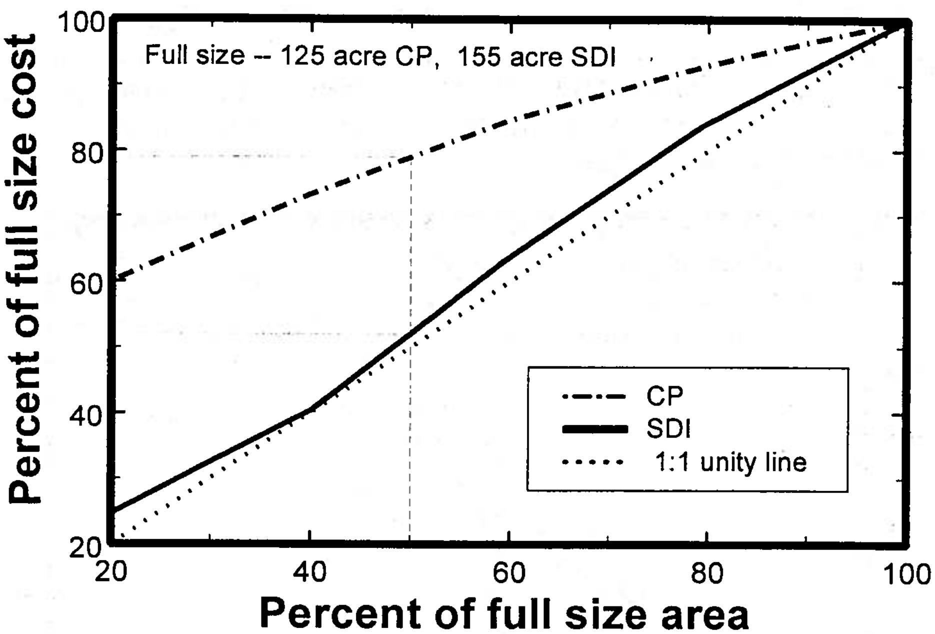

Figure 9. CP and SDI system costs as related to field size. (after O'Brien et al., 1997)

Economic comparisons of CP and SDI systems are sensitive to the underlying assumptions used in the analysis (Lamm et. al., 2003). The results show that these comparisons are very sensitive to size of CP irrigation system, shape of field (full vs. partial circle CP system), life of SDI system, SDI system cost with advantages favoring larger CP systems and cheaper, longer life SDI systems. The results are moderately sensitive to corn yield, corn harvest price, yield/price combinations and very sensitive to higher potential yields with SDI with advantages favoring SDI as corn yields and price increase. A Microsoft Excel spreadsheet template to make CP and SDI economic comparisons is available for downloading from the internet for free at http://www.oznet.ksu.edu/sdi/Software/SDISoftware.htm

SYSTEM LIFE OF SDI

SDI system life must be at least 10-15 years to reasonably approach economic competitiveness with full sized center pivot sprinkler systems that typically last 20-25 years. Using careful and consistent maintenance, a 20 year SDI system life appears obtainable when high quality water from the Ogallala aquifer is used. The system performance of the K-State SDI research plots has been monitored annually since 1989 with few signs of significant degradation. The benchmark study area has received shock chlorination approximately 2-3 times each season, but has not received any other chemical amendments, such as acid. The water source at this site has a TDS of 279, hardness of 189.1, and pH of 7.8. This water source would be a moderate chemical clogging hazard according to traditional classifications (Nakayama and Bucks, 1986). It is possible that the depth of the SDI system (16-18 inches) has reduced the chemical clogging hazards due to less temperature fluctuations and negligible evaporation directly from the dripline.

CONCLUDING STATEMENTS

Research progress has been steady since 1989. Much of K-State's SDI research is summarized at K-State's SDI Website at http://www.oznet.ksu.edu/sdi/

Irrigators are watching the results of K-State closely. Some irrigators have begun to experiment with the technology and most appear happy with the results they are obtaining. It is K-State's hope that by developing a knowledge base in advance of the irrigator adoption phase that the misapplication of SDI technology and overall system failures can be minimized. Economics of the typical Great Plains row crops will not allow frequent system replacement or major renovations. Irrigators must carefully monitor and maintain the SDI system to assure a long system life.

Continued or new areas of research are concentrating on optimizing allocations of water, seed, and nutrients, utilizing livestock wastewater, developing preliminary information about SDI use with other crops besides corn, water and chemical application uniformity, and finally system design characteristics and economics with a view towards system longevity.

ACKNOWLEGEMENTS

Several K-State faculty members in addition to the author have conducted and contributed to the progress of KSU SDI corn research over the years since 1989. These include, Bill Spurgeon, Todd Trooien, Harry Manges, Danny Rogers, Mahbub Alam, Loyd Stone, Alan Schlegel, Gary Clark, Dan O'Brien, Troy Dumler, Kevin Dhuyvetter, Mark Nelson and Norm Klocke.

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SB 430 - LOCAL CONTROL OR NOT

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PRIOR TO SB 430

In 1972 the Kansas Legislature passed the Kansas Groundwater Management District Act. This act was designed to allow local landowners and water users more influence in groundwater management decisions when they formally organized met all the criteria set out in the act. It was never intended to give locals complete autonomy in resource decisions, but few argue that the intent was to significantly increase their involvement and influence. The opening section of this act, the legislative declaration, says it best:

"K.S.A. 82a-1020. Legislative declaration. ...It is the policy of this act to preserve basic water use doctrine and to establish the right of local water users to determine their destiny with respect to the use of groundwater insofar as it does not conflict with the basic laws and policies of the state of Kansas...."

In crafting the procedures of how locals would determine their own destiny, the Legislature provided 19 district powers. Two of these powers most directly relating to this paper were: 1) the power to adopt and enforce standards and policies relating to groundwater management which are not inconsistent with the GMD Act or state law; and 2) the power to recommend regulations to the chief engineer of the division of water resources which are necessary to enforce the policies of the board.

There have been two plausible interpretations of these powers that have been discussed over the years. One is a recognition by the Legislature that the GMD's would be dealing with all groundwater management issues - including the water right issues covered within the Water Appropriation Act, and, all other groundwater issues within the authorities of other state agencies (most notably the Kansas Department of Health and Environment). The specific power to recommend regulations through the chief engineer was to address all the water right issues, while the specific authority to adopt and enforce local policies was the tool intended to address all the other (non-DWR) groundwater management issues.

The second interpretation postulated that the districts were given two enforcement tools for water rights issues, and one enforcement tool for non-water right issues. For the water rights issues the two enforcement tools were: 1) to adopt formal regulations (making their local water rights policies state law); and/or 2) to locally adopt "policies" for local enforcement. The first option being more formal and legally defensible while the latter option would be more flexible, but less legally defensible. For the non-water rights issues the districts could only adopt a local "policy" and could only locally enforce it via the courts. Either way, no one seemed to be interpreting these powers as being contradictory to each other - that is until the 2001 Legislature.

The 2001 Legislature felt that the GMD's should not have the authority to adopt and enforce local policies and amended KSA 82a-1903 to require all GMD, non-administrative policies to be placed into formal regulations. They cited the court case of Bruns vs the Board of Technical Professions for their justification. This case declared that state agencies could not have enforceable policies when they had the authority to promulgate regulations, as policies were not publicly developed and they could circumvent the regulation process. The GMD's argued that the Bruns decision was correct for state agencies with the authority to promulgate regulations, but that it was not on point in that the GMD's had no authority to promulgate regulations (only recommend same to a state agency). There was no reason to bring the GMD's under mandatory regulation requirements, and there was no conflict in the two GMD powers they sought to reconcile.

Due to some technical language problems in the original 2001 legislation amending KSA 82a-1903, the 2002 Legislature also introduced HB 2710, designed to correct the missed intentions of last year's bill. This bill was eventually amended into SB 430.

House Substitute for SB 430

SB 430 began on January 24, 2002 as a simple bill to amend the disability certification procedures for certain hunting permits. In March, 2002 the House amended SB 430 to substitute a new bill concerning GMD's and their powers. This became House Substitute for SB 430. (The original hunting issues under SB 430 were amended into SB 504). Eventually House Substitute for SB 430 was amended again to include language concerning several issues desired by the Rural Water Districts, and to incorporate the HB 2710 corrections.

Finally House Substitute for SB 430 ended up (relative to GMD's only): a) requiring all GMD's to place all non-administrative policies into regulation form. Regulations to be recommended to DWR were required by January 1, 2003, and all others by January 1, 2004; b) restricting the GMDs' power to adopt and enforce local polices to only *administrative* policies; c) giving the GMD's the power to recommend groundwater-related regulations to other state agencies in addition to DWR; and d) allowing the GMD's to enforce locally recommended regulations to state agencies by suitable action, administrative or otherwise.

Post House Substitute for SB 430

There is little argument that House Substitute for SB 430 changed the way Kansas GMD's do business. Whereas before the GMD's could recommend regulations to the chief engineer, they could also adopt and enforce local policies if he or she would not adopt recommended regulations, or would try to unduly influence them. Now the GMD's ***must*** recommend regulations to the state agencies - who can adopt them, or not. This arrangement has increased the state's influence over local GMD activities significantly.

One disadvantage of SB 430 is the fact that all GMD regulations are technically regulations of the state agency adopting them, and must be enforced by that agency since this law did not adequately provide a local enforcement mechanism. Since the GMD's had been assuming selected enforcement responsibilities of the state agencies prior to SB 430, they had the ability to direct agency manpower and dollars elsewhere. This has been raised as an issue to Governor Elect Sebelius' BEST process.

Another disadvantage is the effect this legislation may have on the development and implementation of the Kansas Water Plan's new Ogallala Management strategy. This new plan calls for the GMD's to divide the Ogallala up into aquifer sub-units, prioritize these into high, medium and low priority sub-units, set groundwater budgets to reduce the declines, and finally implement enhanced management programs to reach the budget goals. Local monitoring and enforcement of these programs will likely be prominent issues. With no local capabilities in these regards, what incentives do the GMD's have to aggressively develop solutions? Moreover, with limited budgets and manpower, what incentives do the state agencies have for adopting and assuming local regulations for active local programs?

Issues still remaining after SB 430 are:

1) It is clear the legislature intended for the GMDs to be capable of enforcing their regulations. The language they provided in the act, however, turned out to be inadequate to allow this. The 2003 Legislature needs to be receptive to correcting their earlier language.

2) The Legislature also intended that the state agencies process the GMD proposed regulations in a reasonable length of time. Their law says:

"Within 90 days after receipt of a final draft of proposed rules and regulations recommended by a groundwater management district, the chief engineer shall: (1) Approve or reject the proposed rules and regulations for adoption; and (2) either initiate procedures pursuant to the rules and regulations filing act to adopt the approved proposed rules and regulations or return the rejected proposed rules and regulations, together with written reasons for the rejection, to the groundwater management district."

At least 2 of the state agencies are interpreting this language such that the 90 days does not start until the proposed regulations are in final form for public hearing. This interpretation will allow the state agencies to completely ignore locally proposed regulations until the GMD board agrees to any and all state wording changes. The legislature also needs to address this issue as well.

CONSERVATION PROVISIONS OF THE 2002 FARM BILL

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FARM SECURITY AND RURAL INVESTMENT ACT OF 2002

- Represents the single most significant commitment of resources toward conservation on private lands in the nation's history
- Places strong emphasis on the conservation of working lands, ensuring that land remain both healthy and productive
- Provides farmers and ranchers with voluntary conservation programs commensurate with regulatory challenges they face
- Builds upon past conservation gains
- Responds to the call for a balanced portfolio of tools for conservation, including technical assistance, cost-sharing, and land retirement

PROGRAMS

Environmental Quality Incentives Program (EQIP)
Wetlands Reserve Program (WRP)
Wildlife Habitat Incentives Program (WHIP)
Farmland Protection Program (FPP)
Private grazing land, technical assistance
Conservation Security Program (CSP)
Conservation Innovation Grants
Technical Service Providers (TSP)

ENVIRONMENTAL QUALITY INCENTIVES PROGRAM (EQIP)

Key Points

- The Natural Resources Conservation Service (NRCS) accepts applications throughout the year.
- NRCS provides technical and financial assistance. Technical service providers could provide technical assistance.
- An EQIP plan of operation and contract that has been approved by NRCS is required.

Key Changes

- Funds to be used are allowed in the first year of the contract.
- The total maximum allowable payment amount is increased to $450,000 over the life of the Farm Bill.
- "Bidding down" to increase ranking is eliminated.
- The animal numbers cap on large confined animal feeding operations is eliminated. All animal feeding operations are eligible for assistance.
- A Comprehensive Nutrient Management Plan (CNMP) as a necessary practice for assisting feedlot operations is defined.
- An incentive payment to develop a CNMP is allowed.
- Ground and surface water conservation is provided for.

Environmental Quality Concerns

Air Quality - Excessive wind erosion
Air Quality - Livestock Management
Grazing Lands Health
Water Quality - Concentrated, non-confined animal waste
Water Quality - Confined animal waste
Water Quality - Nutrient, pesticides, or sedimentation
Water Quantity - Ground and surface water conservation

GROUND AND SURFACE WATER QUANTITY CONSERVATION PROGRAM

The purposes of this program are the following:

- To improve irrigation systems
- To enhance irrigation efficiencies
- To convert to production of less water-intensive agricultural commodity or to dryland farming

Quote from the law

"...assistance will facilitate a conservation measure that results in a net savings of ground or surface water resources in the agricultural operation of the producer."

Funding

In Fiscal Year (FY) 2002, Kansas received $3.4 million for financial assistance for the High Plains Aquifer Region.

The FY 2003 budget allocation has not been received at the time of this writing.

Eligible Lands

In FY 2002, eligible lands must lie within a township that contains a portion of the High Plains Aquifer.

In FY 2003, the area may be expanded to other irrigated areas. The final rule has not been issued at the time of this writing.

REQUIREMENTS OF WATER CONSERVATION PROGRAM PARTICIPATION

If land continues to be irrigated:

- The producer must currently have or will install a functioning state-approved water meter to state specifications (K.A.R. 5-1-6) before cost-share dollars are disbursed to the producer.
- The producer must use an approved evapotranspiration (ET) based scheduling system. The producer will not exceed the calculated ET by 10 percent the first year of the contract and will not exceed the calculated ET by 5 percent the remaining years of the contract.
- The well capacity must be able to meet the seasonal Net Irrigation Requirements (NIR) with 50 percent chance rainfall for the crop grown.
- On the contract acres, the producer will stay within the certified rate and amount of existing water right at the time the Environmental Quality Incentives Program (EQIP) contract is signed.
- An end gun shall not be used on a center pivot sprinkler system.
- The producer shall not irrigate more land than the reported five-year average of irrigated acres.
- The irrigation water amounts that the producer reported to the Division of Water Resources (DWR) will be used to determine the bench mark condition for net water savings. The producer will furnish the reports from the previous three years to determine the average bench mark water volume.

We anticipate that there will be more sign-ups and requests for assistance than funds available; therefore, we have established the priority ranking system below. The ranking is based on reducing water use from surface and ground water with the major emphasis placed on ground water--specifically the Ogallala Aquifer and connected aquifers such as the Equus Beds. The greatest savings in water use is obtained by converting (1) irrigated land to dryland for the life of the contract and (2) inefficient surface irrigation systems to low pressure center pivots or subsurface drip irrigation (SDI).

In FY 2002, there were 690 applications totaling about $27 million. Only 82 applications were funded using the $3.4 million allocated to Kansas. In northwest Kansas, 104 applications were received in the nine counties and only nine were approved. In Kansas, only the applications in the "High Category" with a priority of 1 or 2 were funded.

Therefore, a producer has a better chance of obtaining funds if his or her application involves (1) a conversion to dryland farming (discontinuing irrigation), (2) a change to crops that demand less water, and (3) the installation of irrigation systems that are more efficient in providing water to the plant roots.

HIGH CATEGORY

Priority No. 1

The land will be converted from irrigated to dryland, starting with the first full cropping season of the contract.

Proper wellhead protection must be installed around the "discontinued" well(s) to protect the ground water. The producer must verify that the water rights will not be used elsewhere.

Priority No. 2

The producer will install a three-year crop rotation that will reduce water use by 50 percent. The producer will stay within a three-year average of 1.5 years of the NIR for corn (using 80 percent chance rainfall).

Example:

Thomas County, growing corn, using a center pivot with drop nozzles (90 percent efficiency)

Thomas county NIR (80 percent chance) for corn = 15.4 inches
(15.4 inches x 1.5 years) / 90 percent pivot efficiency = 25.7 inches for 3 years

Priority No. 3

The producer will upgrade the irrigation system to increase the irrigation efficiency by 25 percent or more. Use National Engineering Handbook (NEH) Part 652, Irrigation Guide, Table KS6-1 to determine the existing and planned irrigation efficiencies and record the change in efficiencies.

MEDIUM CATEGORY

Priority No. 1

The producer will install a three-year crop rotation that will reduce water use by 40 percent. The producer will stay within a three-year average of 1.8 years of the NIR for corn (using 80 percent chance rainfall).

Priority No. 2

The producer will upgrade the irrigation system to increase the irrigation efficiency by 15 to 24 percent and determine the change in efficiencies using NEH Part 652, Irrigation Guide, Table KS6-1.

LOW CATEGORY

Priority No. 1

The producer will install a three-year crop rotation that will reduce water use by 30 percent. The producer will stay within a three-year average of 2.1 years of the NIR for corn (using 80 percent chance rainfall).

Priority No. 2

The producer will upgrade the irrigation system to increase the irrigation efficiency by 10 to 14 percent and determine the change in efficiencies using NEH Part 652, Irrigation Guide, Table KS6-1.

Priority No. 3

The producer's current system is at least 85 percent efficient using NEH Part 652, Irrigation Guide, Table KS6-1, and the producer will begin to use an ET-based irrigation scheduling system.

The producer will be asked to provide additional data during the application (sign-up) process such as acres converted to dry cropland, acres converted to permanent vegetation, acres converted to a less water-intensive crop, acres converted to a more efficient system such as SDI and center pivot, and new application acres of ET-based scheduling.

A person can submit an application at any time, meaning that EQIP has a "continuous sign up" period. At publicly advertised dates, there will be a cutoff when no further applications will be accepted for consideration in the ranking for each of the resource concerns. For 2003, Kansas is planning to set a cutoff date once the final rules are published and money has been allocated to each state.

For each cutoff period, all applications on file in the state will be ranked. Contracts will then be awarded in accordance with the above priority system until the money allocated for the given resource concern has been expended.

An application can be modified or cancelled at any time prior to each cutoff date. Unless the application is withdrawn, it is re-ranked for each subsequent application cutoff.

CONTRACT PRACTICES FOR WATER QUANTITY

When an application has been accepted, a contract is developed. The contract contains the conservation practices that the applicant intends to apply to address the resource concern. This may include pipelines from the well to the location of the center pivot or SDI system. There are also incentives for management practices that include conservation crop rotation and irrigation water management.

The attached table lists the FY 2003 cost-share practices and rates for Kansas.

CONTRACT DURATION

The contract requires that at least one practice be installed in the first years of the contract. After all practices are completed, the contract must be continued for one additional year for maintenance. If all practices are completed the first year of the contract, then the contract will be a two-year contract to provide for maintenance. For center pivot and SDI systems, the participant is required to follow an ET-based scheduling program (such as KanSched) for the two years. If the person does not stay within the allowable application rate and also show water savings over the life of the contract, then he or she may be out of compliance with the contract. NRCS staff and Kansas State University county extension personnel are available to work with the participants to keep the water use within acceptable limits. Management may dictate growing different crops during part of the contract in order to stay within allowable water use limits for the life of the contract.

If an incentive practice is included, then the contract must be a minimum of four years. There is payment for the incentive the first three-years, and the fourth year is maintenance. For example, if irrigation water management (IWM) is selected, then the participant will receive $10 per acre the first three years; and in the fourth year, the person is still required to apply IWM for maintenance.

For more information, visit your local USDA Service Center or check our website at http://www.ks.nrcs.usda.gov

STATE IRRIGATION EFFICIENCY COST-SHARE PROGRAM

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STATE CONSERVATION COMMISSION

The State Conservation Commission (SCC) was established by the Kansas Legislature in 1937 to promote soil and water conservation. The SCC is governed by nine members consisting of an elected commissioner from each of the five administrative areas; two ex-officio members representing Kansas State University (KSU) Research and Extension; and two appointed members representing the Kansas Department of Agriculture (KDA) and the USDA, Natural Resources Conservation Service (NRCS). The agency is administered by an executive director appointed by the commissioners.

The SCC has the responsibility to administer the Conservation Districts Law (K.S.A. 2-1901 et seq.), the Watershed District Act (K.S.A. 24-1201 et seq.) and other statutes authorizing various programs. The agency budget is financed from the dedicated funding of the State Water Plan Special Revenue Fund, State General Fund, and fee funds.

The agency is structured as a single program agency, but operates several subprograms that tie both to the mission of the SCC and to many stated goals of the State Water Plan. One of the goals of the SCC is to administer efficiently those subprograms that enhance and protect the state's natural resources. The agency pursues this goal by working with the 105 conservation districts and 88 organized watershed districts, and other local, state and federal entities.

WATER RESOURCES COST-SHARE PROGRAM

The Water Resources Cost-Share Program (WRCSP) was authorized by an amendment to K.S.A 2-1915 in 1979 and was first funded in 1980. The conservation district in each county administers the program at the local level. The SCC develops regulations, policies, and procedures to guide program implementation.

Each fiscal year, beginning July 1, county conservation districts receive an allocation of cost-share funds from the SCC. A portion of these funds may be used for a variety of conservation practices. Other allocated funds may only be used to address a specific resource concern such as water conservation. These targeted funds are called the Irrigation Initiative Allocation (IIA).

The SCC and conservation districts are assisted in implementation of the program by the NRCS. With the a few exceptions, all structures or practices cost-shared through the WRCSP are required to be built to NRCS "Standards and Specifications."

IRRIGATION EFFICIENCY PROGRAMS

The Kansas Water Plan has identified groundwater declines as an issue in the Lower and Upper Arkansas, Cimarron, Upper Republican, Smoky Hill-Saline and Solomon River Basins. In 1993, the Kansas Agriculture Ogallala Task Report recommended the SCC provide enhanced cost-share assistance for irrigation system efficiency improvement. Through dedicated funding of the WRCSP, the SCC provides enhanced cost-share funds through the IIA to 38 conservation districts to provide financial assistance to irrigators for eligible efficiency measures designed to improve or convert existing irrigation systems. Targeted areas of highest priority for irrigation system modification under the WRCSP include the Rattlesnake Sub-Basin and the Intensive Groundwater Use Control Areas (IGUCA's). The goal of providing financial assistance in the form of cost-share and management incentive payments is to reduce consumptive use.

Conservation District Eligibility

The IIA funds are allocated based on those counties with greater than 24,999 acres of irrigated land and greater than 24,999 acre feet of water irrigated as reported to the Division of Water Resources water use reports. Currently, 38 county conservation districts primarily in the western one-half of the state are eligible to receive IIA funding.

Eligible Practices

The following is a list of eligible practices offered under the state irrigation efficiency cost-share programs:

- Low Energy Precision Application (LEPA)
- Low pressure spray nozzles
- Subsurface drip irrigation
- Irrigation tailwater recovery system
- Irrigation water conveyance pipeline
- Irrigation Management Incentive (payment/not cost-share)

Eligible Applicants

Eligible applicants include landowners, tenants or operators. Tenants and operators must have authority granted by the landowner through a power of attorney. Application is made at the county conservation district office. All applications must be approved by the SCC before a project may begin. Applications for irrigation efficiency cost-share are received by the conservation district during a specified sign-up period then evaluated and prioritized based on efficiency improvement. Potential Farm Efficiency for irrigation practices adopted by the SCC is defined in the NRCS Kansas Irrigation Guide.

Limitations

The following limitations apply to irrigation efficiency cost-share applications:

- A valid water right (in good standing) must be verified to the conservation district.
- Cost-share funds can not be used to convert non-irrigated land unless an equal amount of previously irrigated land is taken out of irrigated production.
- The proposed project must have a minimum final cost per acre foot saved based on a state prioritization worksheet.
- Cost-share rates are set by the conservation district at a maximum of 70% of the actual cost or county average cost, whichever is less.
- State established cost-share limits are $10,000 per practice unless set lower by the conservation district. (Exceptions may be made for subsurface drip projects.)
- Non-metered systems and systems with end guns are eligible but for a lesser amount of cost-share.
- All applicants must review and sign a conservation plan of operations.

Subsurface Drip Irrigation

The SCC promotes the adoption of subsurface irrigation technology through enhanced funding opportunities for interested applicants. In fiscal year 2002 the SCC funded 16 demonstration sites in 10 counties at a cost-share rate up to $20,000 per system. Multiple co-sponsors of these projects included NRCS, KSU Research and Extension, Groundwater Management Districts, irrigation equipment dealerships, banks and county conservation districts. Although demonstration projects are not being pursued by the SCC in fiscal year 2003, an increased level of funding up to $20,000 per system may be available based on state prioritization criteria.

Irrigation Water Management Incentive

In fiscal year 2002, the SCC began a pilot project that provided monetary incentives to irrigators to implement an evapotranspiration (ET) based irrigation scheduling program. The intent of this program is to provide awareness and education to irrigators to encourage adoption of irrigation scheduling technologies such as KanSched. The SCC requires participants to receive appropriate training from KSU Research and Extension or the NRCS in order to gather, enter and process data required to implement a scheduling program. This program has been adopted for statewide eligibility for FY 2003.

WRCSP FUNDING

Funding Source

Funding for the Water Resources Cost-Share Program comes from the Kansas Water Plan Special Revenue fund, which is generated from an assortment of taxes and fees. This fund is a dedicated source of state funding with the intent of protecting, conserving and enhancing Kansas' natural resources.

FY 2003 Funding

The base allocation in the amount of $2,751,608 was divided among the 105 conservation districts in fiscal year 2003. This allocation addresses locally identified needs that may also be used to address water conservation. The 38 Kansas conservation districts eligible for enhanced irrigation efficiency allocations received a total of $451,000 to implement irrigation efficiency practices. The Rattlesnake Sub-basin is allocated $25,000 in irrigation efficiency targeted funding. An additional $213,871 is available on a competitive basis for Subsurface Drip (SDI) Irrigation demonstration projects.

THE NEED TO INTEGRATE EQUIPMENT FOR CENTER PIVOT APPLICATION OF ANIMAL WASTES

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SUMMARY:
A discussion of why the integration of equipment for land application of animal wastes is important will be presented. Examples of projects will be discussed along with what worked, what did not work and why.

OBJECTIVE:
To help people involved with the land application of animal wastes have an appreciation for the need to apply an integrated approach to designing, specifying and purchasing equipment.

INTRODUCTION:
Land application of wastewater with center pivot equipment has been used for more than thirty years. Until the late 1970's the land application package was easy to select as the choices were limited to relatively high pressure impact sprinklers (50psi) or the Valley Slurry Shooter™ using high volume sprinklers (90psi). Since the early 1980's the equipment and techniques for irrigating with fresh water have changed dramatically to the point the pressures at the nozzle inlet may be as low as 6psi. Utilization of these packages requires close spacing of application devices and water relatively free of particles as the size of the orifices are small. In addition animal production units have changed in the number of animal units in single facilities, type of collection and storage and the amount of scrutiny from the public. Midwest Plan Service's MWPS-30 (MWPS, 1999) discusses general principles in sprinkler selection relating to fresh water application but does not attempt to quantify any procedure or specifically look at the integration of equipment for wastewater application. Other publications have provided general discussions with of components without offering information on integration - Livestock Waste Facilities Handbook (MWPS, 1993), Liquid Manure Application Systems Design Manual (NRAES, 1998) and Agricultural Waste Management Field Handbook (USDA, 1992). LaRue and Dorset began a discussion of a procedure to begin the integration process with *SELECTING SPRINKGER PACKAGES FOR ONLAND APPLICATION OF REUSE WATER (ASAE 1999)* and reported at the 2001 Central Plains Irrigation short course.

Then becoming even more important in today's world we must take into account the issues and public perception of land application systems. Land application of wastes may be imposing in some locations, potentially dangerous conditions relative to environmental quality (Hegde 1997). We must insure any equipment being used for land application meets public scrutiny and local, state and federal regulations.

DISCUSSION:

Currently many land application systems are pieced together using what is available and adding equipment, which may not be applicable to a wastewater application. In particular, sprinkler packages are selected by customers and irrigation dealers based on personal experience and preference without regard to the rest of the system. The application for a permit to apply animal wastes is considered a nuisance and just enough is done to "get by". Generally little consideration is given to the overall needs or limitations of the system. The components of a system for the land application of wastewater are animal type, collection, storage, treatment, pumping, distribution, land application and management

An approach for the integration of equipment does not exist. Experience has taught, "if it worked the last time, it should work again" or "that is what my neighbor's doing" or "it works for my freshwater". We recommend looking at each waste water system from collection through application to make the best selection of equipment to provide an integrated package.

1) To begin the process, information must be collected far upstream of where we typically look - type of livestock, housing, collection, storage, treatment and pump suction position. Examples may be:

swine, farrowing, confinement, lagoon, floating suction
dairy, free-stall, scraper, lagoon, suction on the bottom

2) Next we need to consider the characteristics of the material being applied - estimated solids content, daily flows, organic material, inorganic materials, what the customer wants to pump - liquid or solids (dependent on permit and design parameters) and particle size

3) Lastly one of the areas most ignored - management issues such as goal or objectives for the system, permit requirements, operating and energy costs and interest in expansion.

Most of these items are not applicable or important to successful freshwater irrigation system.

Let us look at some examples to see if adequate consideration was given to the items in 1, 2 and 3 above.

Example 1 – Dairy, free stall, collection by scraping, two small lagoons – storage only, no water collected from rain, short of labor, energy cost not critical, has been using a traveling gun but labor is a problem, wants to use a towable center pivot.

Customer contacted irrigation dealer who contacted Valmont about what sprinkler package to use. Recommendation was made to use the Valley Slurry Manager™ with Nelson volume guns.

How did it work – within two hours of starting the pivot, the pivot pipeline was completely plugged and the customer was less than happy.

What went wrong?

1) customer was using a Cornell pump designed for solids handling and passing large chunks, ¾ inch and larger
2) pump suction was on the bottom of the lagoon
3) little agitation was done prior to beginning pumping
4) solids content was high for land application through irrigation equipment

What was done to correct?

1) customer switched to a Cornell slurry pump
2) pump inlet was set up off of the bottom
3) agitation was started 24 hours before pumping and moved to different positions around the lagoon
4) rainwater was diverted from the roofs of his buildings into the lagoons

How has it worked – fair – customer is satisfied.

Example 2 – Swine, farrowing, slatted floors, lagoon for 180 days of storage, short of labor, energy cost not critical, neighbors critical, has been using slurry wagons

Customer contacted irrigation dealer who contacted Valmont about what sprinkler package to use. Recommendation was made to use drops and a low pressure sprinkler package with Rotators on the first part of the pivot and fixed pad sprinklers on the outer end with wind and rain shutoff sensors.

How did it work? – fair but customer started moving pump between fields creating performance issues.

What went wrong?

1) No consideration was given to long-term customer needs
2) Annual use requirements were not adequately defined

What was done to correct?

1) Simplified the pump hookup to facilitate moving the pump

2) Specified another pump to better meet a broader range of conditions
3) Revised sprinkler package recommendation to meet a broader range of conditions.

How has it worked – ok – customer is satisfied and understands limitations of using the same pumping system everywhere

Example 3 – Swine, integrated system, slatted floors, lagoon for 180 days of storage, short of labor, energy cost not critical, neighbors critical, has been using slurry wagons

Customer was contacted by swine producer who sold him on the idea of the advantages of the wastewater – value as water, nitrogen and phosphorous source. Customer agreed and swine producer tied pipeline into the center pivot.

How did it work? – poor – plugged pressure regulators on the pivot sprinkler package

What went wrong?
1) Irrigator did not understand all of the ramifications of using waste water
2) Swine operator placed pump suction on the bottom of the lagoon

What was done to correct?
1) Irrigator changed his expectations – uniformity, first span
2) Sprinkler package was changed
    a. eliminate the use of pressure regulators
    b. wider spacing for water application devices in the first span allowing the use of larger orifices
3) pump suction was raised off of the bottom

How has it worked – ok – irrigator is satisfied and understands limitations when pumping wastewater

Example 4 – Dairy, free stall, flushing, lagoon for 20 days of storage, short of labor, energy cost not critical, limited neighbor issues, has been using slurry wagons, customer has irrigation well also

Customer contacted irrigation dealer who contacted Valmont about what sprinkler package to use. Recommendation was made to use the Valley Slurry Manager™ and Komet volume guns.

How did it work? – good for waste water but customer became unhappy when suffered yield loss during an abnormally dry year due to the lower distribution uniformity of the volume gun package for freshwater.

What went wrong?

1) Customer expectations
2) Did not adequately explain system limitations

What was done to correct?
1) Solutions offered were not accepted due to costs
2) Currently not resolved

How has it worked – ok – except when very dry

Example 5 – new installation, dairy, free stall, flushing, separator, two lagoons for 120 days of storage, short of labor, energy cost not critical, neighbors critical, plans to apply through center pivot

Dairyman contacted neighbor who irrigates. Irrigator contacted irrigation dealer who suggested a sprinkler package. Irrigator then contacted Valmont about what sprinkler package to use. Recommendation was made to drops and use Nelson Trashbusters.

How did it work? – not installed yet due to an impasse between the dairy and the irrigator. Dairy wants to send water primarily and handle separated solids by spreading in the fall, irrigator wants nitrogen and phosphorous besides the water and is concerned about problems with spreading solids.

What is going wrong?
1) Dairyman's expectations
2) Irrigator's expectations

How has it worked – ask me in another year!

SUMMARY:

This discussion has been to help develop an appreciation of the need to apply an integrated approach to the design and application of irrigation equipment for wastewater utilization. From the examples it is clear the problems, which may be experienced if an integrated approach is not utilized. In most of the examples the expectations were not met initially due to the lack of understanding of the total system. Livestock operators, irrigators, irrigation equipment dealers and manufacturers need to develop a greater appreciation for the total impact of all factors in a wastewater design including the animals, collection, storage, treatment, pumping, distribution, land application and management.

Please remember to always observe and follow all applicable local, state and federal regulations and apply good environmental stewardship.

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Utilizing Swine Effluent on Sprinkler-Irrigated Corn

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ABSTRACT

The expansion of large swine production facilities in Colorado prompted a need to evaluate the impact of swine effluent applied on irrigated corn grown on sandy soil. The objectives of this study were to: evaluate the use of swine effluent as a nutrient source for irrigated corn production, evaluate irrigated corn response grown on sandy soils to different application rates, determine NH_3 loss during sprinkler application and the 72 hour period following application, and evaluate N movement through the soil profile under swine effluent and commercial-N fertilizer for irrigated conditions. The 5-year study was initiated in 1995 on a 14.5-ha sprinkler-irrigated field planted to grain corn. In 1999, the field experiment was expanded to two other facilities, both having one-stage lagoons to evaluate ammonia volatilization from single stage lagoon effluent. Both swine effluent and commercial-N fertilizer treatments were applied at four N rates labeled, control, low, agronomic, and high. All treatments were replicated three times in a randomized complete block design. Approximately 90% of the total nitrogen from the 2-stage lagoon effluent was in ammoniacal form, and the total dry matter content of the effluent was only 0.1-0.2% by volume. Corn yields increased with the increase of both swine effluent and commercial-N fertilizer rates. In contrast to the swine effluent treatments, significant soil-N buildup was observed at the 1.5 to 3.0 m depths for the commercial-N fertilizer treatments. Higher total N and P plant removal for the swine effluent treatments resulted in little N accumulation below the root zone. As the swine effluent application rate increased, the plant N and P removal and recovery rate increased. Ammonia loss during application ranged from 8 to 27% of the total NH_4-N in the effluent due to drift and volatilization, with an average loss of 17%. The range of estimated N loss from the soil within 72 hours of application varied from 24 to 56%, with an average loss of 42% of the NH_4-N in the applied effluent. The total N loss from both the sprinkler application and the soil ranged from 33 to 73% of the applied NH_4-N, with an average loss of approximately 60%. Effluent N concentration did not significantly impact the percent of N lost, while air temperature and wind speed were significant variables in the percent of N lost.

INTRODUCTION

Animal wastes produced by confined swine feeding operations can be a valuable source of nutrients for crop production. However, when manure is used under irrigated conditions, an increased potential for nutrient runoff or leaching occurs, especially on sandy soils. Recent expansion of concentrated swine production facilities in eastern Colorado has increased concerns about potential nitrate (NO_3-N) contamination of the Ogallala Aquifer, the sole source of water for drinking and irrigation in the area.

Concentrated swine production facilities in the area commonly utilize one- or two-stage lagoon systems where effluent must be removed from the lagoon periodically to prevent overflow. Effluent from second-stage lagoon is typically utilized for flush water. Sprinkler application of swine effluent to crop fields is the most common way to utilize these materials. Over-application of lagoon effluent, combined with irrigation or precipitation in excess of crop evapotranspiration, has been implicated in NO_3-N leaching below the root zone.

A five-year study was conducted to evaluate the potential impacts of swine effluent application on irrigated, sandy soils in eastern Colorado. The objectives of this study were to: 1) evaluate the use of swine effluent as a nutrient source for irrigated corn production, 2) evaluate corn yield response to different application rates, 3) determine the amount of mineral N available to the crop over a series of swine effluent application rates, effluent sources, and field conditions and 4) evaluate N movement though the soil profile under swine effluent and commercial-N fertilizer for irrigated conditions.

MATERIALS AND METHODS

The study started in the spring of 1995 on a swine production facility and grain farm in Yuma County, Colorado, and continued through the 1999 growing season. The primary study field was on a 14.5 ha center pivot irrigated field located near a swine production facility with a 4,000-head annual capacity. In 1995 and 1996, the facility was a swine finishing unit, and in 1997 switched to breeding sows. The waste generated from the animals was stored in a two-stage anaerobic lagoon system. A 50-gallon per minute commercial well was used to supply water mainly for animal use and limited flushing of the animal waste to the first lagoon. However, effluent from the second lagoon recycled every 8 hours to flush the animal waste to the first lagoon. Field experiments at the one-stage lagoon sites were conducted at a 2-year old operation 15 km south of Burlington, CO and at a 6-year old operation facility 30 km north of Wray, CO. Soil of both Yuma and Wray sites was Valent sand, while the Burlington site was on a Satanta loam.

The primary study site was under continuous corn production prior to 1995, and was fertilized with commercial-N fertilizer only. The site was a circular field under sprinkler irrigation (center pivot) divided into 3 pie-shaped replications. Each replication contained 4 treatments, including 3 swine effluent rates plus a control. Swine effluent treatments and the control were assigned to each replication randomly using a randomized complete block design. Swine effluent was applied on the field using a sprinkler (center pivot) system by pumping effluent from the second cell of the two-stage lagoon through an underground pipe to the center pivot. Effluent from the first cell flowed into the second cell via gravity through a PVC pipe with an inlet at 1.5 m below the water surface (lagoon depth was 6 m). The solid content of the effluent from the second cell was 0.1-0.2% by volume. The effluent application rates were estimated based on the agronomic N requirements for irrigated corn, according to Colorado State University recommendations for irrigated grain corn production. The low (L) and high (H) rates were 56 kg N ha^{-1} below and above estimated agronomic N. The control (C) received only 28 kg N ha^{-1} of commercial-N fertilizer, as a starter, was applied at planting time.

Glass jars containing 10 ml (8%) H_2SO_4 were used to collect swine effluent samples for each plot by placing them on a metal post 1.6 m above the ground. Four jars were used per plot. After the pivot passed over each plot, effluent samples were transferred to clean plastic bottles, capped, and immediately stored in a cooler until analysis. At the same time, four effluent samples were taken from the pipe (at the pump) that transports effluent to the field, mixed, sub-sampled, and placed in clean acidified sealed plastic bottles and placed in a cooler.

After the pivot passed over each plot where effluent was applied, soil samples 0-2.5, 2.5-5.0, 5.0-7.5, 7.5-15.0, and 15.0-30.0 cm deep were taken in a pre-designated sub-plot of 0.8 x 0.8 m within the main plot where the initial soil samples were taken. Seven to 10 soil cores per depth increment were taken with a stainless steel hand probe, combined, placed into clear plastic bags, and transferred immediately to a cooler. The first soil-sampling period immediately after effluent application was designated 0-h (hours after application), and sampling was repeated 24, 48, and 72-h after effluent application. All soil and effluent samples were analyzed for NH_4-N and NO_3-N using zinc reduction and automated phenate method at the Colorado State University Soil Testing Lab. Ammonia loss during application was calculated as the difference between NH_4-N concentration of the swine effluent pumped from the lagoon and NH_4-N concentration collected in an acidified solution in a glass jar under the pivot. The ammonia loss from the soil was estimated as the difference between soil NH_4-N content at a given time after effluent application and the initial soil NH_4-N mass prior to applying swine effluent. Air temperature, soil temperature, and humidity were measured on site during each application and sampling time using portable digital humidity and temperature devices.

RESULTS

Swine effluent nutrient analysis

Ammonium-N represented on average approximately 90% of the total nitrogen for the two-stage lagoon, where total dry matter was only 0.1-0.2% by volume. Effluent analysis from a two-stage lagoon containing waste from swine finishing units in 1995 and 1996, and swine breeding units in 1997, revealed large differences, especially for NH_4-N and P concentrations (Table 1). Another difference observed was that the concentration of micronutrients from the finishing units was greater than the concentration of the breeding units' effluent.

Table 1. Average of effluent analyses from one-stage and two-stage lagoons†.

		-------- Two-Stage Lagoon --------			One-Stage Lagoon§	
Constituent	Unit	1997	1998 ‡	1999	1999A	1999B
NH_4-N	mg L^{-1}	218	334	209	351	610
NO_3-N	mg L^{-1}	0.24	0.24	0.68	0.87	1.6
Total N	mg L^{-1}	223	340	215	368	639
Total C	mg kg^{-1}	1,025	---	1,060	1,720	1,117
pH	——	7.6	---	7.8	7.5	8.0
Solids	mg kg^{-1}	1,200	---	1,000	2,500	6,100

† Two-stage lagoon effluent is from breeding units and one-stage effluent is from finishing units.
‡ In 1998, only the analysis of nitrogen is available.
§ Lagoon A is one year old and Lagoon B is 6 years old.

The analysis of swine effluent also showed considerable temporal variability in nutrient concentration at different times during the crop growing season. The analysis showed that the N content decreased late in the growing season. This decrease was due to the high use of fresh water in the flushing system late in the growing season, as compared with early in the season. Also, during the first year of the study, the rate of application was designed to be 1.25, 2.5, and 5.0 cm of effluent due to high initial residual soil-N. In 1996 and 1997 the rates were increased to meet the designed N rates to 2.5, 5.0, and 8.0 cm of effluent based on the residual soil-N and effluent nitrogen content. Interestingly, no foliar burn was observed at any rate or application time over the 4-years of this study.

Corn yield response to swine effluent

Yield performance of irrigated corn increased with the increase of effluent application rates across all three years. The highest rate of swine effluent did not significantly increase grain yield over the recommended agronomic rate (Table 2). However, poor weather conditions, such as cool temperatures and hail damage, affected plant growth and grain yields in 1995 and 1996, as compared to the 1997 growing season, where growing conditions were more optimal. The total amount of rainfall received between May and August during 1995, 1996, and 1997 was 46, 48, and 37 cm, respectively. Cooler than normal temperatures and 3-4 events of high rainfall (>4.0 cm) occurred between early May and mid-August in 1995 and 1996, while only one high rainfall event occurred in early August of 1997. These conditions contributed to relatively low yield performance in 1995 and 1996.

Table 2. Grain yield of irrigated corn under swine effluent treatments.

Effluent Rates	Total N Available†	Yield 1995	Yield 1996	Yield 1997
	kg ha^{-1}			
Control	84	2195	2634	2759
Low	151	5707	4264	8215
Agronomic	207	7212	7400	11288
High	263	7713	8529	12229
$LSD_{(0.05)}$		3382	2695	2875
P>F(0.05)		0.0256	0.0059	0.0580

† Total amount N available for effluent includes credits from soil-N, organic matter, starter-N, and irrigation water-N. Differences between treatments greater than LSD value are significant at alpha= 0.05.

Corn grain yields increased with the addition of commercial-N fertilizer up to the agronomic rate. The increase in N rate by 56 kg N ha^{-1} above the agronomic rate did not produce a significant increase in grain yields. Yield difference between years was primarily a function of weather conditions. The trend of yield response to commercial-N fertilizer rates was similar to those of swine effluent.

Swine effluent can alter soil properties, such as AB-DTPA extractable soil-P, pH, and EC. The AB-DTPA extractable P increased in the top 15 cm as the swine effluent application rate increased. However, during the first year of swine effluent application no significant increase in extractable P value at the top 15 cm for all rates was observed, as compared to the initial level prior to swine effluent application. The increase in P value was significant after 3 consecutive years of swine effluent application, especially under the high application rate. Soil pH did not change in the top 15 cm during the 3 years of swine effluent application. On the other hand, soil EC increased slightly in the top 15 cm after the second and third year of swine effluent application. The average EC value was 0.3 dS m^{-1}, which is not considered high according to soil salinity standards.

Soil N profile after 3 years of swine effluent application

Residual soil-N distribution in the soil profile after 3 years of swine effluent application at different rates showed no significant differences in residual soil-N at all depths. The residual soil-N after harvest was significantly lower for all swine effluent treatments, as compared to the initial residual soil-N prior to the first effluent application in 1995. The decrease in residual soil-N content after 3 consecutive years of swine effluent application was due to soil-N removal by the crop (Fig. 1). This was evident where continued increase in plant-N removal under swine effluent treatments was observed from 1995 to 1997. Soil-N buildup was greater for the high rate of effluent application in the top of the soil profile. The cumulative residual soil-N in the 1.5-3.0 m zone for all swine effluent application rates was greater than in the root zone (0-1.2 m). Approximately 20 kg N ha^{-1} accumulated below the root zone. This accumulation may suggest a potential for N leaching below the root zone, where N is beyond the typical plant rooting depth.

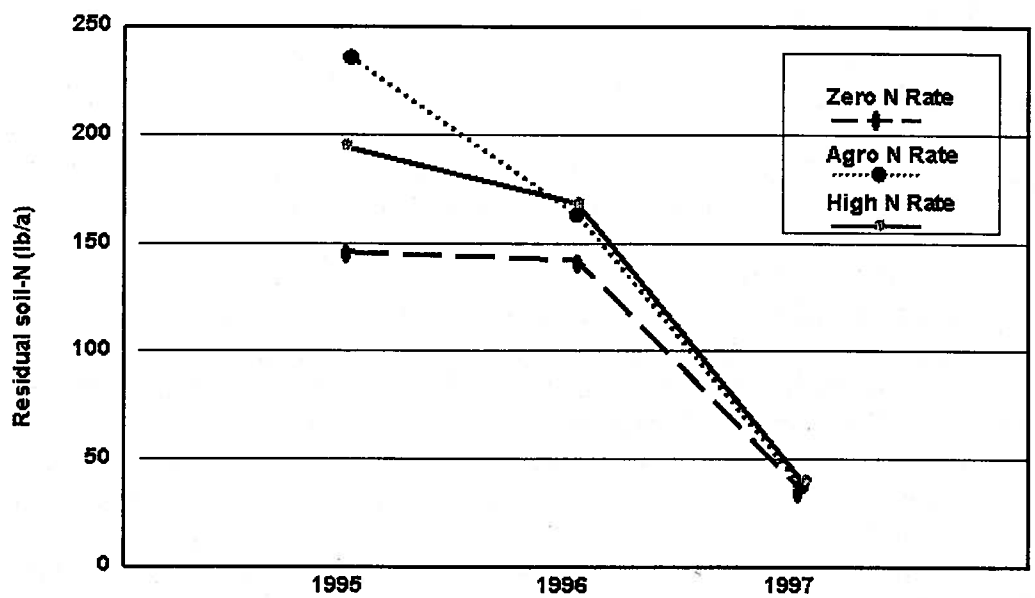

Figure 1. Residual soil-N in the 0-10 ft. soil profile under different effluent application rates.

Ammonia loss from sprinkler and soil

Ammonia loss during sprinkler application accounted for 8-27% of the total NH_4-N applied, while NH_4-N loss from the soil system accounted for an additional 24-56% (Table 3). Ammonium-N concentration was greater in the one-stage lagoons compared to the two-stage lagoon. However, NH_4-N loss on a percentage basis from effluent pumped from both types of lagoon systems (one and two-stage) was not significantly different for Yuma and Burlington on May 3 and 6, 1999. At the 2.5 cm application rate, sprinkler N losses from the two-stage lagoon at Yuma and the one-stage lagoon at Burlington were 21.8 and 20.7%, respectively. Soil N losses at these same sites and time were also not significantly different (38.2 and 42.5%), in spite of the differences in soil texture (sand vs. loam). This indicates that similar weather conditions resulted in similar total percentage of N losses, regardless of effluent source or concentration. However, N loss during different application times of effluent was significantly different. This can be attributed to great differences in weather conditions (i.e., air temperature, wind speed, soil temperature, humidity, etc.) during the times of applications of different months. Effluent source (one- vs. two-stage lagoon) had no influence on the percent of N loss during sprinkler application or from soil surface. This indicates that the percent of N loss due to volatilization was source independent, but weather condition and time of application were the major factors in N loss.

Effluent application rate did not affect the percent of N lost during sprinkler application. The average of N loss during sprinkler application from 1.3 cm h^{-1} application rate was 13.8%, while it was 12.8% from the 1.9 and 2.5 cm h^{-1} application rates. In contrast, N loss from the soil during the first 2-h after effluent application was significantly affected by effluent application rate. The 1.3 cm application rate resulted in a significantly greater percent of soil N loss compared to 2.5 cm application rate, 2-h after application. On the other hand, the rate of NH_4-N loss declined sharply after the 24-h sampling period for all application rates. A comparison of the three application rates (1.3, 1.9, and 2.5 cm) reveals no significant differences in additional NH_4-N loss at 24, 48 and 72-h after application. The total cumulative N loss from both sprinkler and soil was significantly different, however. These results have practical implications for producers as they attempt to manage NH_4 emissions from swine operations. Soil incorporation is currently the recommended best management practice following effluent application, yet producers typically must wait at least 24-h on sandy soils and up to 72-h on fine textured soils before soil moisture conditions are optimal for operating field equipment. By this time, roughly 50% of the applied N may be lost.

Effluent application during cool and calm weather increased the amount of N received at the soil surface, where the percent of NH_4-N loss was the smallest compared to applications during June and July. The greatest N availability was observed during November, where 58-66% of applied NH_4-N was available 72-h after application. High application rates resulted in greater N availability compared to low application rates, for the majority of sites and times of applications. Therefore, cool season applications at high rates can result in excess soil N and a greater potential for N leaching. Conversely, effluent application during warm, windy weather can lead to greater NH_3 volatilization and reduced N availability, resulting in potential crop N deficiencies. These differences in measured N losses and N availability can result in N excesses or deficiencies if not properly accounted for. Thus, farm managers need to use the appropriate N availability estimates for each time of application in order to determine the correct effluent application rate in their nutrient management planning.

Table 3. NH_4-N lost during application and from the soil (% of total applied) as a function of application rate at different sampling periods averaged across all sites and years.

Application Rate	NH_4-N Lost During Sprinkler Application	Soil Inorganic-N Loss at Different Hours After Effluent Application				Total Inorganic-N Loss
		2-h	24-h	48-h	72-h	
(cm h^{-1})	%					
1.3	13.9	27.3	7.8	6.4	5.3	60.7
1.9	12.8	22.6	10.3	6.6	5.4	57.7
2.5	12.8	13.4	8.4	8.0	5.7	48.3
LSD(0.05)	5.3	6.5	4.3	3.9	3.6	7.1

CONCLUSIONS

Several important aspects of utilizing swine effluent became apparent from this study. The N in swine effluent from two-stage lagoons was almost entirely (90%) in the ammoniacal form (NH_4-N). This is important because ammonium-nitrogen is immediately available to the crop, unlike organic forms of N found in many other waste products. Therefore, managing swine effluent-N becomes very similar to managing commercial-N fertilizer under irrigated conditions. The main difficulty in constructing a nutrient management plan is in determining the appropriate rate of ammonia volatilization.

We found that producers can expect to loose up to 25% of the NH_4-N in effluent just during sprinkler application in the summer months. Another 45% of the total NH_4-N in the effluent may subsequently be lost from the soil surface within 72-h after application during the hot months of the year. During cold weather, we observed sprinkler application losses of approximately 10% and soil losses of an additional 25% of the total NH_4-N applied. From this, producers can infer that approximately 30% of the NH_4-N in swine effluent applied during the summer is available for crop utilization, while up to 65% of the NH_4-N in effluent applied in the winter months is available. These N loss rates are consistent with previously published results (Sharpe and Harper, 1997; Safley, et al., 1992).

Increased N application by 56 kg N ha^{-1} above the recommended agronomic rate did not produce a significant yield increase under swine effluent or the commercial-N fertilizer. Total plant N and P removal increased as the swine effluent application rate increased. The increase in total N and P removal with the increase of the effluent application rate contributed to the increase of grain yields. This increase in N removal resulted in lower residual soil-N after three years of effluent application and less potential of N movement below the root zone. The N and P concentrations in the swine effluent were highly variable over time as a function of the waste flushing system, especially with the two-stage lagoon system. Therefore, the rate of N and P loading was highly variable.

Applications of swine effluent at different times during the growing season appears to be an effective way of managing swine effluent under irrigated conditions when it is applied through a sprinkler system, as no plant leaf burn was observed, even at high application rates. Sprinkler-applied swine effluent at the recommended agronomic rate resulted in higher yields and minimal N accumulation below the crop root zone.

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IRRIGATING WITH SWINE EFFLUENT

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INTRODUCTION

Nebraska swine annually produced manure containing 40 million pounds of nitrogen. The trend toward increased concentration of animals in large production units makes it difficult to find enough available land for economical manure distribution at agronomic application rates. In Nebraska, pigs per farm have increased from 250 in 1982 to 507 in 1997. As the number of pigs per enterprise has increased, there has not been a corresponding increase in the number of acres per enterprise available for land application and crop utilization of the stored swine manure.

The goal of our research was to evaluate alfalfa as a nitrogen sink for swine effluent. Data from our experiment has shown that alfalfa receiving 600 pounds of swine effluent nitrogen per acre removed about 100 pounds more nitrogen per acre than alfalfa receiving no swine effluent. Established, irrigated alfalfa can remove more than 700 pounds of nitrogen per acre in the harvested hay (Table 4). The implication is that producers can reduce the land base for effluent distribution by more than 50% when compared to the 200 pound removal rate for corn followed by winter rye (Table 4). This could be beneficial to producers who do not have sufficient land to apply effluent at agronomic rates to corn or other row crops.

Additional advantages to alfalfa are: it covers the ground all year round which reduces the erosion potential; the nitrogen use curve is more constant through the season than for annual crops; uptake of phosphorus and potassium are relatively high; effluent application can occur at times that are not possible in a corn system; and alfalfa is deep rooted and can scavenge nitrogen from deeper in the soil than most other crops grown in Nebraska.

METHODS

A line-source sprinkler system was used to distribute a range of effluent rates to both alfalfa and corn. Figure 1 shows the distribution of the effluent and of fresh water. The experiment was designed so that the distribution patterns of both the fresh and effluent waters produce an even amount of water application. Therefore, only effluent rates changed. Rates of effluent were chosen that provided from 0 to 140% of the predicted nitrogen harvest for the corn-winter rye and alfalfa treatments. Irrigation of each crop could be controlled and was applied based on soil moisture and crop nitrogen needs with the caveat of needing to apply up to 600 lb-N per acre near the centerline.

Laboratory analysis showed that the effluent contained about 90 lbs. total nitrogen, 100 lbs. K_2O, and 10 lbs. P_2O_5 per acre-inch of water (Table 1). The goal was to apply sufficient effluent so that at the end of the growing season both the corn and alfalfa would have plot areas with an excess of applied N. In 1994, soil samples, leachate and crop harvest took place at 6 equally spaced areas across each cropping system plot for a range of 0 to 140 percent of nitrogen application versus estimated harvest removal.

At each sampling site a porous cup extractor was installed 6.5 feet in the ground (Insert, Figure 1). The soil water solution passing the cup was sampled and analyzed for nitrate. Neutron readings were recorded to determine the rate of water flow past the 6.5 foot depth. This information was used to determine the amount of nitrate leaching at each sampling site (Table 3).

The original alfalfa stand was planted in the fall of 1992 and replanted in 1993. In 1996 the corn-rye and alfalfa areas were switched. However, the gradient of increasing levels of swine effluent remained the same. In 1996, a non-nodulating alfalfa variety (Saranac) was planted along with the conventional variety and the number of subplots was reduced from 6 to 5 (Figure 1). Unlike the conventional variety, the non-nodulating isoline could not use atmospheric nitrogen for crop growth needs.

In each year, alfalfa samples were collected from each subplot using a flail-type forage harvester. Sampling protocol was designed to mimic a range of harvest management schemes. Thus, each replicate contained subplots that were harvested 3x, 4x, or 5x times per year. The 3x treatment was harvested at full bloom and the 4x and 5x at tenth bloom. The 5x treatment had the 5th harvest after a killing frost. Plant dry matter was collected from a 30 square foot area and used to estimate total dry matter production for the treatment. Laboratory analysis provided the N content in each alfalfa sample.

1996 was 75 lbs total nitrogen/acre. Actual N removal in the forage was within 10 lb-N per acre for the non-nodulating and nodulating isolines (Table 4).

A severe winter in 1996 caused winter kill in the experiment, so the alfalfa was replanted in 1997. Subsequent work continues to support the notion that non-nodulating alfalfa will produce forage of the same quality and quantity as nodulating alfalfa if N is applied to meet crop needs. Failure to apply sufficient N tends to reduce plant stand by allowing weed competition, and it appears to increase the potential for winter-kill in the isoline we tested. Plant breeding efforts will likely reduce the winter-kill problems.

DISCUSSION

Documenting the environmental effects of swine effluent application is the major objective of this research. Two indicators have been monitored 1) soil nutrient levels in the spring and fall and 2) nitrate leaching.

Using book-values, 9 tons of alfalfa would remove about 500 lb-N, 135 lb-P_2O_5, 540 lb-K_2O per acre. In 1994, laboratory analysis of the dry matter indicated that about 700 lb-N were removed in the forage. Field data indicate that alfalfa can remove more applied N than a more traditional crop like corn. Thus, the lagoon water can be distributed over fewer acres of land when alfalfa is used as a scavenger crop.

Soil samples taken in the spring of 1997 indicated that a buildup of both phosphorus and potassium at the higher application rates was occurring (Table 5). The phosphorus levels were increasing despite removal at rates up to 50 lb-P_2O_5 per acre greater than the application rate. Research evaluating the long term impacts of manure applications have suggested that manures high in NH_4-N can change soil pH sufficiently to allow additional phosphorus to enter the available pool from the organic pool. In addition, increased microbial activity tends to increase P mineralization rates. Both of these factors are likely present in fields where swine lagoon water is applied. Thus, long term application of swine lagoon water may need to account for the additional P in the management plan.

Potassium application was in excess of the removal rate so a buildup was anticipated. However, continued buildup of soil potassium could cause soil structure problems in the future. At some point, effluent might need to be reduced until potassium levels decrease.

Leaching of nitrate may occur when drainage through the soil profile occurs. When irrigation scheduling techniques are used correctly, drainage is held to a minimum. When rainfall is greater than crop use, drainage is inevitable. Research using commercial fertilizer applications tend to suggest that off-season losses are a definite concern in Nebraska. So even if good irrigation

RESULTS

In 1994, dry matter production ranged from 9 to 10 tons of alfalfa per acre. Thus, the addition of 560 lb-N resulted in an additional ton of dry matter production (Table 2) and a slight increase crude protein of about 1.5% (data not shown). Yields were highest when the alfalfa was harvested 4 times per season at approximately 10% bloom. Apparently, the harvest after a killing frost reduced yields for the 5x treatment.

Subsurface drainage was greater than would be typical of a field managed using irrigation scheduling techniques (Table 3). This was due in large part due to near normal precipitation and below normal temperatures so little irrigation was necessary. Drainage ranged from 6 inches in plots receiving no lagoon water to 4 inches in plots receiving 560 lb-N. This reduction in drainage is attributed to the additional production (1 ton/ac) resulting from the lagoon water application.

The N concentration of soil water at the 6.5 foot depth had flow-weighted average concentrations that ranged from 4.9 ppm in plots receiving no lagoon water to 37 ppm where 560 lb-N were applied (Table 3). The acceptable N concentration is up for discussion, however, if the maximum contaminant level for drinking water of 10 ppm NO_3-N is used, our data would suggest that approximately 340 lb-N could be safely applied to irrigated alfalfa. We were not in a position to estimate losses of N to the atmosphere during and after application, but published values are typically greater than 30%. Assuming 30% application loss, the actual removal in the alfalfa dry matter would be close to 235 lb-N. This level of utilization agrees with laboratory research from Minnesota that suggests that alfalfa will preferentially fix up to 2/3 of the N removed in the forage. This happened despite N applications that would have met crop needs. Thus, a high percentage of the N contained in the alfalfa forage will continue to be fixed from the atmosphere.

Nitrate leaching losses ranged from 7 to 33 lb-N per acre (Table 3). Though a zero tolerance rule could be applied, these levels are within the range recorded for crops fertilized with commercial fertilizer. Leaching losses would be reduced if subsurface drainage could be reduced by irrigation management strategies that allow plants to lower soil water content near the end of the season. Another beneficial practice would be to leave room in the soil profile for rainfall by accounting for the deep rooting depth of the crop. Both of these practices were not possible during this research due to timely rainfall events and the need to apply 6-7 inches of lagoon water.

In 1996, the non-nodulating alfalfa nitrogen harvest was 70 percent of the nodulating alfalfa at the zero effluent rate, but equal to the nodulating alfalfa at the higher nitrogen rates. Due to it being a crop establishment year, sufficient rainfall, and the use of irrigation scheduling, the maximum nitrogen applied in management is practiced, over application of N may lead to leaching losses. This is of particular significance where manure storage capacity considerations necessitate land application regardless of soil water availability, thus, increasing the risk of a drainage and N leaching event.

Application of swine effluent to alfalfa shows considerable promise based on the results of this research. Alfalfa uses large amounts of nutrients contained in animal manures and provides ample opportunities to spoon feed applications in much the same was as commercial fertilizers. Further development of the non-nodulating alfalfa isolines will enhance the value of alfalfa as a crop suitable for use in crop rotations used by animal producers.

Acknowledgments

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Table 1. Nutrient concentrations of monthly water samples collected from the swine lagoon in parts per million. Concord, NE.

Year	No. Sample	Total N	NH_4-N	P_2O_5	K_2O	S	Zn	Na	Ca	Mg
		-------	-------	-------	ppm	-------	-------	-------	-------	-------
1993	12	400	310	9.8	401	4.1	0.13	103	59	23
1994	12	420	371	12.8	554	2.1	0.14	114	65	26
mean		410	340	11.3	472	3.1	0.13	108	62	24

Table 2. Mean dry matter yields as affected by swine effluent application in1994. Concord. NE.

Effluent N Rate	Alfalfa Harvests per Season 3x	4x	5x	Mean
lb N / acre	--------------------	tons DM per acre	--------------------	--------------------
0	8.5	9.3	8.9	8.9
90	8.3	9.7	9.1	9.0
210	8.4	10.4	9.5	9.4
340	8.4	10.0	9.7	9.3
450	8.7	10.7	10.0	9.8
560	8.8	10.1	10.3	9.7

Table 3. Total nitrogen harvested after irrigation with swine effluent as alfalfa hay and in a corn/rye system. Concord, NE.

Year	Alfalfa type	Nitrogen	Crop	Nitrogen
		lbs/acre		lbs/acre
1993	Nodulating	230 - 250	Corn/rye	154
1994	Nodulating	680 - 745	Corn/rye	213
1995	Nodulating	337 - 520	Corn/rye	162
1996	Nodulating	270 - 383	Corn	205
1996	Non-nodulating	189 - 396		

Alfalfa was established in 1993 and 1996.
Rye cover crop did not survive winter in 1996.

Table 5. Effect of swine effluent application on drainage, leachate nitrate nitrogen and nitrate nitrogen leached. 1994. Concord, NE..

Effluent N-Rate	Drainage	Nitrate-Nitrogen Concentration	Nitrate-Leaching
(lb/ac)	(inches)	(ppm)	(lb/ac)
0	6.3	4.9	7.0
90	5.7	8.2	10.6
210	5.5	8.2	10.2
340	6.3	10.0	14.2
450	4.7	19.9	21.2
560	3.9	37.1	33.1
Mean	5.4	14.1	16.0

Table 4. Effect of lagoon water on soil phosphorus and potassium after four years of irrigation with swine effluent. Concord, NE.

Swine Effluent Application Intensity	Soil P	Soil K
% of estimated N removal	----------ppm----------	
0	31	188
35	42	213
70	51	306
105	70	383
140	66	364

Soil sampled spring 1997; corn grown 1996-97 and alfalfa 1993-95.

Figure 1. Field layout, water distribution and porous cup installation. Concord. NE.