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EVALUATING CENTER PIVOT, NOZZLE-PACKAGE PERFORMANCE

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One definition of performance is: “operation: process or manner of functioning or operating.” The manner of functioning of a center pivot nozzle package is to deliver irrigation water to a targeted area. Good or successful performance in an irrigation setting with a growing crop most often implies that the application of irrigation water accomplished the goal of making the irrigation water available to the crop, usually by being distributed across the soil surface and infiltrated into the crops root zone where it can be accessed by the individual plants equally and, for the case of full irrigation capacity, in sufficient quantities to prevent yield limiting water stress. Another factor related to good performance is minimization of losses associated with the irrigation application, i.e. high irrigation efficiency.

Distribution Uniformity

Distribution uniformity is discussed by Rogers et al. 1997 and illustrated in Figure 1. It and can either indicate the degree of evenness in the depth of irrigation water applied to the soil or in the amount of the water infiltrated into the soil. The former may be associated with depths applied at the surface, based on catch-can measures for sprinkler systems. The latter associated with soil water measurements after infiltration, which are much more difficult to collect than surface measurements. This concept for uniformity was originally developed by Christiansen in 1942 for sprinkler systems. Generally, high uniformity is associated with the best crop growth conditions since each plant has equal opportunity to use applied water. Non-uniformity results in areas that are under-watered or overwatered. In particular, overwatered areas may cause a decrease in irrigation efficiency if the water moves below the crop root zone and therefore is lost for crop water use.

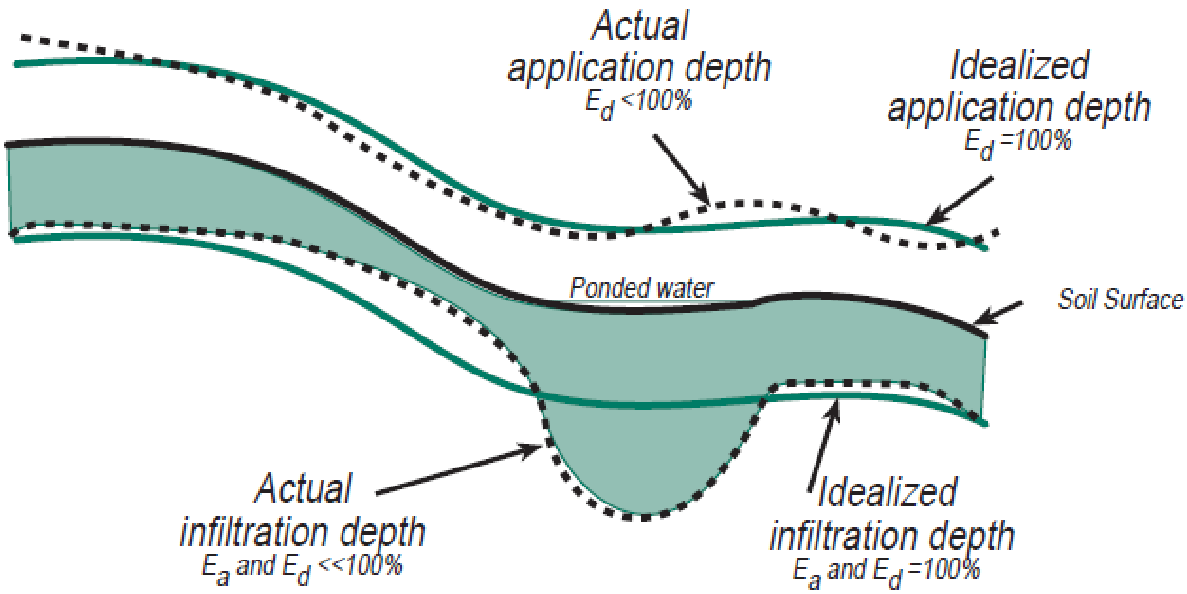

Figure 1: Illustration of a sprinkler package water distribution uniformity verses infiltrated water distribution uniformity in the soil (Rogers et al. 1997).

Irrigation Efficiency

Irrigation efficiency can be defined as the percentage of water delivered to the field that is used beneficially (Rogers et al. 1997). This definition is a broad definition in that irrigation water may have more uses than simply satisfying crop water requirements. Other beneficial uses could include salt leaching, crop cooling, pesticide or fertilizer applications, or frost protection. However, most Kansas irrigation systems are single-purpose, which is to supply water for crop use.

Consumptive Use

Water diverted in Kansas for beneficial use, except for domestic water use, is subject to the terms and conditions of the Kansas Water Appropriation Act. This appropriation act allows the transfer of water use from one type of use to another as long as it does not increase the use of water beyond the original consumptive use. Consumptive use is the amount of water actually consumed while it is being applied to a beneficial use. The amount of consumptive use for various types of users can be large. For example, the consumptive use of water diverted for use in a cooling tower, where it is evaporated, is essentially 100 percent, while water passing through a turbine of a hydroelectric power plant has essentially zero consumptive use. The range of consumptive use for irrigation can be very large as well. For example, large-scale irrigation systems from a river diversion and canal system may have return flows to the river of up to 50 percent whereas a deficit-irrigated field in from a groundwater well in a low rainfall area may have little or no return of water to the groundwater. For many properly-designed and operated irrigation systems in low rainfall areas, consumptive use is often used (or confused) to be crop-water use.

Crop-water Use

An accepted method of estimating crop-water use is through the use of evapotranspiration (ET) which is calculated using weather information. The term evapotranspiration is the combination of two terms, evaporation and transpiration (Figure 2). Evaporation is water which returns to the atmosphere directly from wetted plant surfaces, wetted soil surfaces, or wetted residue cover. Transpiration refers to the water which is transported from soil water reserves through the root system, stems and leaves of a plant before being released to the atmosphere. A primary function of transpiration is cooling of the plant. An additional small amount (around the one percent range) of the water absorbed by the plant is used as part of the photosynthetic process. Nutrients are also transported as water moves from the soil into the plant.

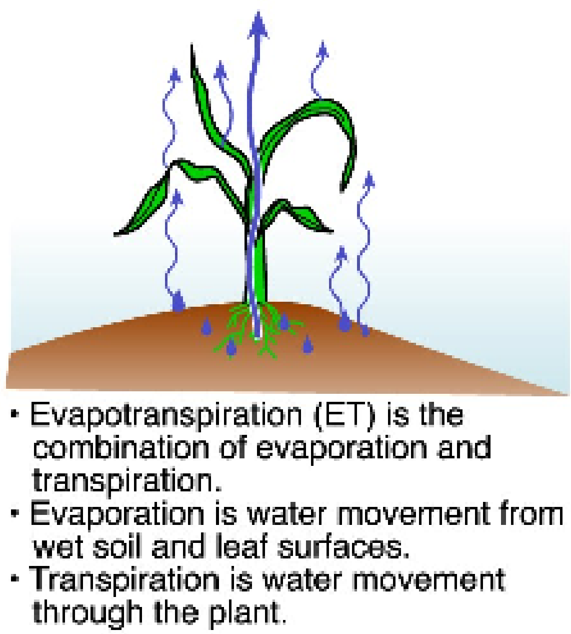

Figure 2: Illustration of evaporation and transpiration (Rogers and Alam, 2007).

It is difficult to measure evaporation (E) and transpiration (T) separately, hence, the combined term, ET. In conventionally-tilled irrigated crops, the E portion of ET is generally about 30 percent of the seasonal crop water budget, but might be cut in half when high, surface-residue tillage systems are used. Early in the season, when the crop is small and does not cover or shade the soil surface, more sunlight and wind energy reaches the soil surface and a higher portion of the ET is the E portion. After the canopy closes, almost all ET becomes T. Evaporation can be suppressed in irrigated agriculture by increasing planting density to encourage rapid ground cover and by minimizing the frequency of canopy wetting by irrigation events when using sprinkler systems. The yield of a crop is generally proportional to the amount of crop-water use.

Modern center pivots and linear-move nozzle packages with proper design and installation and under good irrigation management tend to minimize irrigation losses by reducing the wetted radius of the nozzles and reducing the height of the nozzles above the crop canopy while also selecting and operating the systems to eliminate surface run off. The systems would also be managed to minimize deep percolation. Surface water movement of irrigation water under a center-pivot irrigation system should be eliminated with either a change in the operating procedures or a change in the nozzle-package design. Deep percolation of irrigation can be minimized with proper depth of application and irrigation scheduling; although, total elimination of deep percolation or drainage is not always possible due to the occurrence of large rainfall events. The remaining losses are due to water evaporation while the irrigation water is in flight, on the plant, or on the soil surface. These losses are, in essence, consumed (i.e. returned to the atmosphere).

Water evaporation from a plant surface will suppress transpiration as the evaporation process will serve to cool the plant as illustrated in Figure 3. Canopy evaporation greatly increases during the period of irrigation, so evaporation from surfaces should not be encouraged as the evaporation process occurs much more rapidly than plant transpiration. As much as 0.20 inches of water may be needed to wet a crop canopy. This amount of water could evaporate in several hours while on some days that same amount of water may have been sufficient for the entire day, if it were available for transpiration to the plant via the soil root zone. Therefore, many nozzle-package designs attempt to minimize evaporation losses using various nozzle configurations and placement strategies.

Irrigation water losses, as shown in Figure 4, can be divided into air losses, canopy losses, and soil losses. The center-pivot nozzle package system design and management should minimize (eliminate) surface runoff and deep percolation. Percolation losses may still occur due to unusual precipitation events. Although surface runoff and or water redistribution within a field still occur on some individual fields; in general, surface water losses have decreased over time due to sprinkler package designs which are better matched to field conditions. Also, changing cultural practices such as more adoption of no- or limited- tillage on fields result in high crop-residue covers that reduce the potential for surface run off and early season soil evaporation losses. Deep percolation losses have also been minimized as more irrigators adopt irrigation scheduling as a part of their management practice. There is also an increase in the number of low-irrigation capacity systems (meaning over-irrigation is less likely). Over 90 percent of Kansas irrigated acreage is watered by center-pivot irrigation systems which could, with proper package design and operation, eliminate irrigation water runoff. Deep percolation losses should be minimized

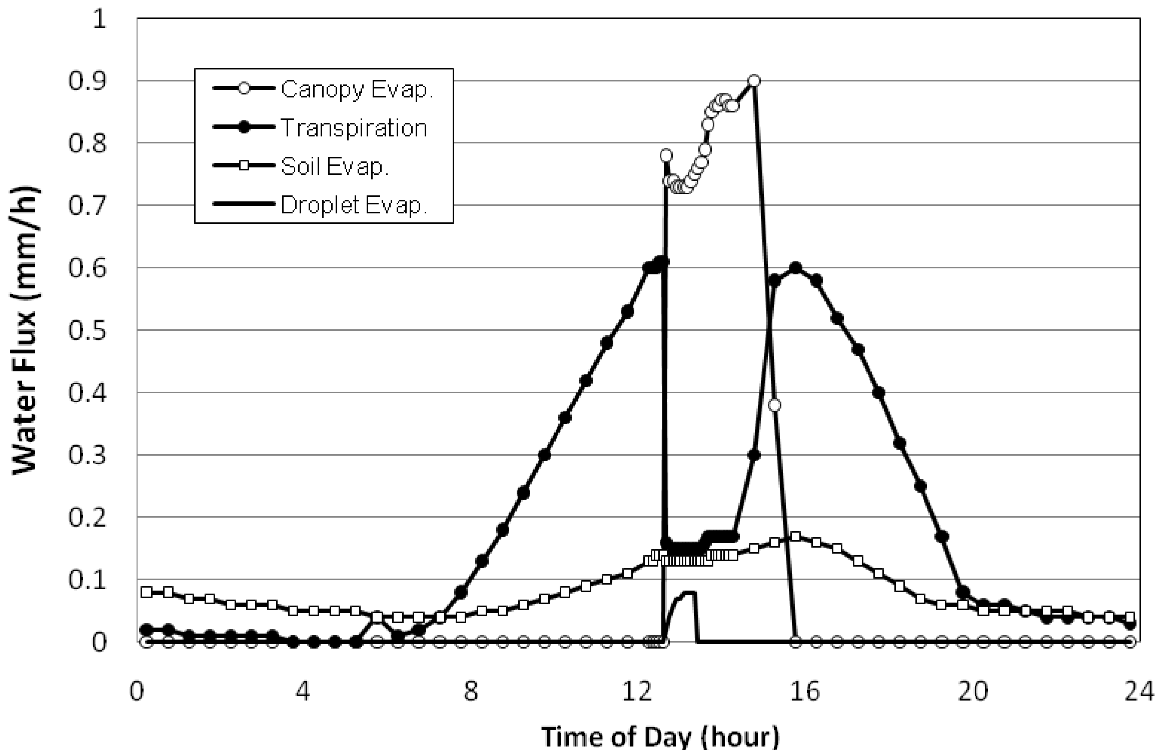

Figure 3. Water use for the rotator sprinkler placed on top the pivot lateral. (Martin et. al 2010).

with proper irrigation scheduling. The remaining irrigation losses as shown in Figure 4 occur either in the air, from the crop canopy, or from the soil. These losses occur as evaporation to the atmosphere, so the irrigation water is consumed just as the water used in the crop transpiration process. The implication of this discussion on water losses for a single irrigation event during the growing season, assuming the system is properly designed and operated (i.e. no surface run off) and properly scheduled (i.e. no deep percolation), then essentially all the water applied would be used consumptively. This implication for a single irrigation event, however, can be different when viewed on a longer time scale, as will be discussed in a later section.

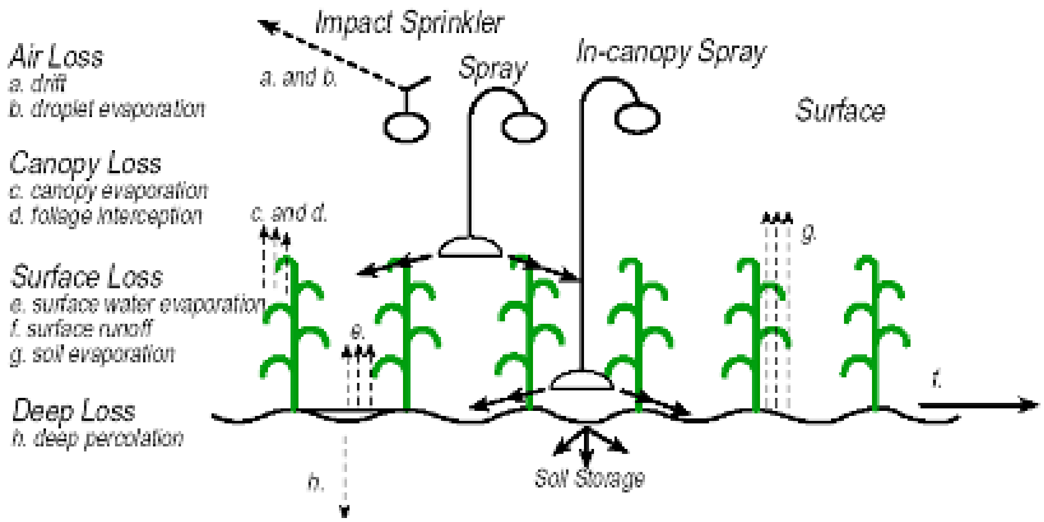

Figure 4: Illustration of where irrigation water losses can occur for a center pivot nozzle package (Rogers et al. 1997).

An example of how irrigation losses can be affected by design criteria is illustrated in Figure 5. Three water-use scenarios are shown for two irrigated conditions and a non-irrigated condition. Note for the non-irrigated condition, no losses of water occurred due to canopy or drop evaporation since no irrigation occurred. There was still some soil evaporation contribution, but there was a high level of transpiration. For the two irrigated conditions, a small sliver is shown to represent droplet evaporation, the evaporation that occurs while the water droplet is in flight. The soil evaporation was greater in the irrigated condition as compared to non-irrigated due to the recently-wetted soil surface from the irrigation. Between the two irrigated conditions, note that the spray just about the crop canopy had less canopy evaporation than the impact sprinkler. Spray nozzles would have a much smaller wetted diameter than the impact sprinkler, and therefore a specific location in a field would have been wetted for less time, resulting in less time for canopy evaporation to occur at that location.

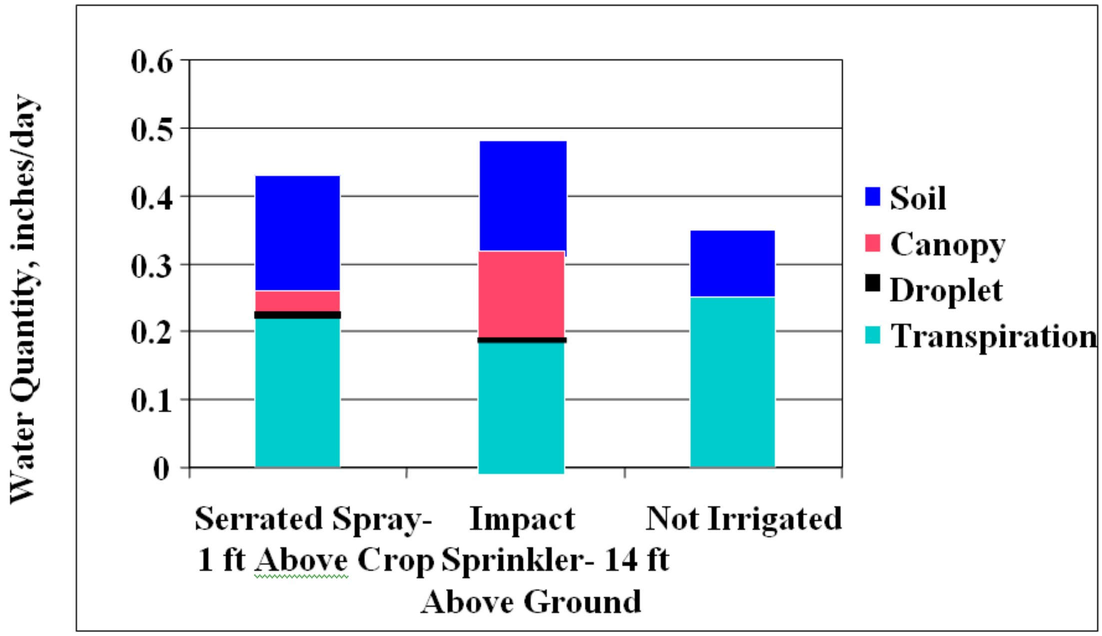

Figure 5: Evaporative losses for impact and spray nozzle devices (Thompson, et al. 1997) Data was collected at Bushland, TX; 90 F, 15-mph windspeed, and dry.

Example of a Center Pivot Uniformity Test

(Text and figure from KSU Bulletin L-908)

When designing sprinkler irrigation systems, it is important to provide as uniform of an application as possible. A non-uniform application will result in areas of under-watering as well as areas of over-watering. This will result in reduced yields as well as decreased system efficiency. The uniformity of the sprinkler nozzle package design is determined by package design. It is affected by the operating conditions, and environmental factors, especially wind. Figure 6 shows the results of a center-pivot uniformity test. Section A of the pivot illustrates a portion of the sprinkler package that was performing well. This area of the pivot has a coefficient of uniformity of almost 90 percent. In section B, a leaky boot connection between two spans was caught in one container. Section C represents the area covered by the outer two spans of the system that shows an area of over watering and under watering. Section D of Figure 6 demonstrates the effect of an improperly-operating end gun. In this case, the operation-angle of the end gun was improperly set and it was over spraying the nozzles of about one third of the last span and the overhang of the center pivot. In this example, all of the causes of the poor uniformity were easily and inexpensively correctable.

Uniformity is decreased if system pressure is not kept at the design pressure. Wear of nozzles and incrustation buildup can also affect the pattern. Canopy interference also affects distribution uniformity.

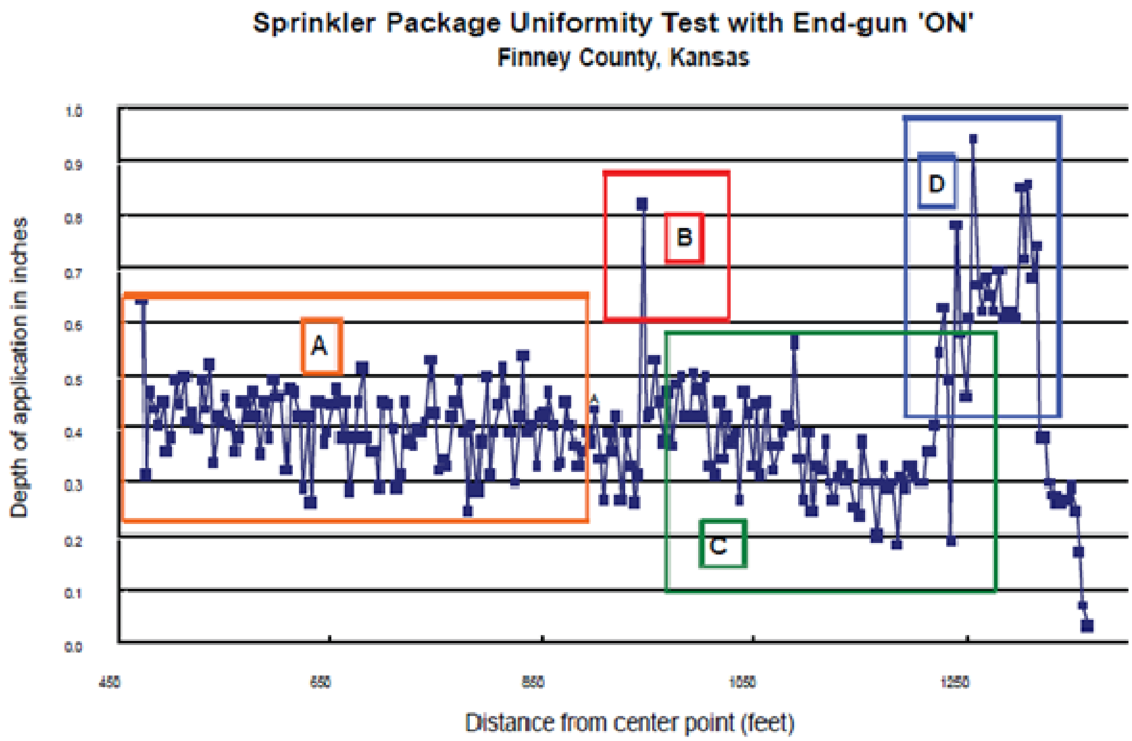

Figure 6: Uniformity test results for a Mobile Irrigation Lab uniformity evaluation (Rogers et al. 2008).

Irrigation Efficiency Impact on Irrigation Schedules and Crop Water Use

Table 1 illustrates the effect of improving irrigation efficiency on the water budget for an example year with average seasonal ET and rainfall for a corn crop. The water budgets were made using KanSched, an ET-based, irrigation-scheduling program (Rogers and Alam, 2008). While the rainfall was near normal for the growing season, it was less than normal early in the season and heavier than normal late in the season. The non-water-stressed ET for the year is 21.13 inches, which would be associated with “full” yield. Three water budgets are shown in Table 1 using a low-capacity irrigation system (1.00 inches/6 days). All field and crop characteristics were identical (118-day corn emerging May 1, loam soil with a 42-inch managed root zone). All irrigation water was scheduled whenever 1.00 inches of root-zone, soil-water deficit existed and the previous irrigation was completed. The only difference between schedules was irrigation efficiencies which were selected to be, 70 percent, 80 percent, or 90 percent.

At 70-percent irrigation efficiency, there were 5 days where the root-zone, soil-water content dropped below the recommended managed-allowable deficient (MAD) of 50 percent. Actual ET was 21.00 inches, which is only slightly suppressed, as compared to “full” ET of 21.13 inches; however, the most severe stress occurred during the pollination period which is the most water-sensitive stage of growth for corn. The lowest predicted root-zone, soil-water level was 39.7 percent of available water. But, since this occurred at pollination, grain yield reduction would likely occur. When irrigation efficiency was increased to 80 percent irrigation efficiency, there were 3 days below MAD and crop ET was increased to 21.09 inches. The lowest predicted root-zone, soil-water level was 46.7 percent of available water. This stress still occurred at pollination, so grain yield reduction might occur, but not to the degree of the previous example. The length and severity of the stress was not as great as the previous example. “Full” ET was still not achieved at 80-percent efficiency but the gross amount of irrigation water was reduced. For the 70- percent efficiency level, 11.00 inches of gross irrigation water was applied as compared to 10.00 inches for the 80-percent efficiency level.

When irrigation efficiency is improved to 90 percent, the crop ET increases to 21.13 inches, which is the maximum for the climatic conditions and maturity length of corn used in this example. This is indicated (Table 1) by noting zero days of soil-water levels below 50 percent MAD. The gross irrigation application dropped to 8.00 inches as compared to the 11.00 or 10.00 inches of the previous examples. It is possible, however, to have examples where increasing irrigation efficiency would not result in reduced gross irrigation application, but it would result in an increase in the amount of water used beneficially by the crop. The drop of 2.00 inches of gross irrigation pumping occurred in this example because the increase in efficiency resulted in more net irrigation water being available to the crop with each irrigation to such a degree that the crop’s full-water requirement was met with a lower gross-irrigation amount.

The data shown in Table 2 represents the case where an increase in irrigation efficiency did not result in a drop in gross irrigation application depth. It uses the same weather record as the example in Table 1; the only change is the soil type and rooting depth. At 70-percent irrigation efficiency, there were 9 days where root-zone, soil-water dropped below the recommended managed allowable deficient (MAD) of 50 percent and the gross irrigation application was 11.00 inches. Increasing efficiency to 80 percent still resulted in 11.00 inches of gross irrigation application, but the number of stress days was reduced to 5 and the level of stress was lower. There was not a reduction in gross irrigation application with an increase in efficiency since all the “saved” water went into meeting the crop-water-use demand.

When irrigation efficiency was increased to 90 percent, one day of crop-water stress was still predicted, even with high efficiency; however, recall the example system is a low-capacity system that can only apply 1.00 inches every six days which could not meet the crop water needs during the extended dry period of this actual weather record. For the entire season, however, more net irrigation water was available due to the higher efficiency resulting in less gross pumping for the season.

In Example 2, increasing irrigation efficiency did not result in a decrease in overall pumpage because both the 70-percent and 80-percent systems pumped 11.00 inches of water. However, the water-use efficiency or water used productively should be improved as the net irrigation application increased from 7.70 inches to 8.80 inches and reduced the number of days that the crop experienced stress. Since the irrigations were scheduled, meaning the water was not applied unless sufficient root zone storage was available, the applied irrigation water should not be lost to deep percolation. This means the loss would be associated with soil, canopy, or air losses which are evaporation processes and the water returned to the atmosphere. This would be "consumed" from the groundwater water source. In this sense, increasing irrigation efficiency did not change the amount of water consumed from the aquifer as the pumped water was either consumed (returned to the atmosphere) by the crop or consumed (lost by the evaporation due to irrigation water losses) by the inefficiencies of the irrigation system. Historically, when the majority of irrigation systems were surface (gravity-flow) irrigation systems, large application depths were required to advance the water across the field in the furrows to ensure the crop root zone was filled along the entire length of the field. This often resulted in deep percolation losses in the upper part of the field and a zone of deep percolation at the end of the field if excess water was diked at the bottom end. Deep percolation losses may have been eventually be returned to the groundwater aquifer. As irrigators in Kansas switched from gravity-flood to sprinkler systems (primarily center pivots), the losses associated with irrigation has switched from deep percolation to surface evaporation losses. These evaporative losses are now considered consumed since these evaporation processes transfer water to the atmosphere and not back to the original water source (aquifer).

Table 1: Effect of improving irrigation efficiency on gross irrigation requirement for corn under a low-capacity irrigation system.

Irrigation Efficiency %	Crop ET Inches	Effective Rain Inches	Gross Irrigation Inches	Net Irrigation Inches	Number of days < 50% MAD	Lowest Soil Water Value
No Irr	17.23	12.57	0.00	0.00	51	16.1%
70	21.00	11.60	11.00	7.70	5	39.7%
80	21.09	11.49	10.00	8.00	3	46.7%
90	21.13	11.52	8.00	7.20	0	52.2%

Table 2: Effect of improving irrigation efficiency on gross irrigation requirement for corn under a low-capacity irrigation system.

Irrigation Efficiency %	Crop ET Inches	Effective Rain Inches	Gross Irrigation Inches	Net Irrigation Inches	Number of days < 50% MAD	Lowest Soil Water Value
70	20.80	12.10	11.00	7.70	9	38.4
80	21.04	11.44	11.00	8.80	5	44.5
90	21.12	11.45	10.00	9.00	1	49.8

Analysis of irrigation consumptive use on an annual basis.

A simulation model was used to examine the effects of several irrigation schedules for two soil types. The average results using multiple years of actual weather data for each of the water-budget components on an annual basis are shown in Table 3. High water-holding capacity, silt-loam soils were used for the northwest Kansas location, while sandy soils were used for the south central Kansas location. The application amounts used for each site were selected as typical for the region. Irrigation was limited to the frequency shown, but it was scheduled based upon available soil moisture (ASM) of 50, 60, and 70 percent, so a range of the total irrigation application amount was applied. A base-line crop was needed to be able to determine how the different water-budget components would change with the addition of irrigation water and what portion of the irrigation water was associated with each change.

For the northwest Kansas location (19.24 inches of average annual precipitation), the average ET for the simulation period was 14.40 inches for the base-line dry-land corn crop. The average amount of runoff for dry-land corn was estimated to be 0.94 inches, with zero predicted percolation and 3.90 inches of interception. As irrigation is added, water budget components increase. Using the three irrigation schedules, irrigation amounts ranged from 13.90 to 16.71 inches and ET values increased according in various amounts above the baseline dry-land value of 14.40 inches. The dry-land water budget components were then subtracted from the corresponding irrigated-condition, water-budget component and are shown in the lower portion of Table 3. For example, for the 50-percent schedule, run off was estimated to be 1.42 inches, however 0.94 inches occurred under dry-land conditions, therefore the increased runoff contribution due to irrigation is 0.48 inches. In the same example, ET increased by 12.34 inches due to the 13.90 inches of irrigation. Dividing these two numbers would be an estimate of the seasonal irrigation efficiency; calculated, in this case, to be 89 percent. The amount of water consumed is estimated by adding ET and interception, since these two amounts are returned to the atmosphere. Percolation could be returned to groundwater. The fate of runoff is less certain, it still might be lost to evaporation, but it was not consumed within the field.

Dividing the amount consumed by the irrigation amount would be an estimate of consumptive use (CU) efficiency, in this example the value is 94 percent.

As additional irrigation water added, both seasonal irrigation efficiency and CU efficiency decrease. Since soil-water levels in the crop root zone are increased, the likelihood of losses to runoff and percolation increase due to occasional large precipitation events within the irrigation season and during the non-irrigation portion of the year.

The results for the south central location (26.08 inches of annual precipitation) on sandy soil follow the same trend as the silt loam example for both seasonal irrigation efficiency and CU efficiency, but the efficiencies are considerably lower. Sandy soils have less water storage capacity and therefore are more prone to have deep percolation losses. Also, the greater annual precipitation south central Kansas provides more opportunities for percolation losses.

Table 3: Water budget comparisons using POTYLDR (Koelliker, 2010) comparisons for two soil types.

	Silt Loam Soil in Northwest Kansas					**Sandy Soil in South Central Kansas**			
Application Amount (inches)	1.00	1.00	1.00	**Dry-land Corn**		0.75	0.75	0.75	**Dry-land Corn**
Frequency in days, if needed	*3*	*3*	*3*			*2*	*2*	*2*	
@ ASM, %	*50*	*60*	*70*			*50*	*60*	*70*	
Irrigation, in.	13.90	15.69	16.71	None		9.39	10.99	12.24	None
Runoff, in.	1.42	1.45	1.52	0.94		1.20	1.27	1.33	1.05
Percolation, in.	0.22	0.44	1.21	0.00		6.38	7.12	8.02	4.05
Intercept., in.	4.68	4.77	4.85	3.90		3.51	3.65	3.74	2.64
ET, inches	26.74	28.18	28.26	14.40		24.33	24.98	25.18	18.34
	Additional amounts as compared to Dry-land Corn								
	Amount of Gross Irrigation Lost					**Amount of Gross Irrigation Lost**			
Runoff, in.	0.48	0.51	0.58			0.15	0.22	0.28	
Percolation, in.	0.22	0.44	1.21			2.33	3.07	3.97	
Interception, in.	0.78	0.87	0.95			0.87	1.01	1.10	
ET	12.34	13.78	13.86			6.03	6.68	6.88	
Eff., % (ET/Irr)	89	88	83			64	61	56	
CU (ET+Intc)	13.12	14.65	14.81			7.77	7.69	7.98	
CU eff, %	94	93	89			73	70	65	

Summary

Center pivot irrigation systems can be equipped with a variety of nozzle packages that can effectively deliver irrigation water to crops. Proper design and operation of the systems are essential for high efficiency and good distribution uniformity. Irrigation application depths, total seasonal application amount, soil type, and precipitation all have an effect on seasonal irrigation efficiency and consumptive use of water.

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