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EFFICIENCY AND UNIFORMITY OF THE LEPA AND SPRAY SPRINKLER METHODS: A REVIEW

A. D. Schneider

ABSTRACT. *Application efficiencies and uniformity coefficients reported for the low energy precision application (LEPA) and spray sprinkler irrigation methods are reviewed and summarized. The relative sizes of the water loss pathways for the two sprinkler methods are also summarized. With negligible runoff and deep percolation, reported application efficiencies for LEPA are typically in the 95 to 98% range. Measurements such as chemical tracers, weighing lysimeter catches, and energy balance modeling are believed to be more accurate than small collector measurements for estimating spray application efficiency. Spray application efficiencies based on these other measurements exceed 90% when runoff and deep percolation are negligible. Because of the start and stop nature of mechanical move irrigation systems, uniformity coefficients for LEPA and spray are measured both along the irrigation system mainline and in the direction of travel. Along the mainline, reported uniformity coefficients are generally in the 0.94 to 0.97 range for LEPA and in the 0.75 to 0.85 range for spray. In the direction of travel, the uniformity coefficients are generally in the 0.75 to 0.85 range for LEPA with furrow diking and in the 0.75 to 0.90 range for spray. On start and stop sprinkler systems, basin tillage on a 2 to 4 m spacing is critical for uniform LEPA irrigation because the basins prevent runoff and average the applications during several unequal start and stop times. Runoff is the largest potential water loss pathway for both LEPA and spray irrigation. For the spray method, runoff can exceed either droplet evaporation and drift or non-beneficial canopy evaporation.*

Keywords. *Sprinkler, LEPA, Spray, Application efficiency, Uniformity coefficient, Runoff, Evaporation, Drift.*

The purpose of this article is to summarize published application efficiency and uniformity data for the low energy precision application (LEPA) and spray sprinkler methods. The size and importance of the water loss pathways for both sprinkler methods and methods for measuring spray application depths will also be evaluated. Heermann and Kohl (1980) presented a detailed review of the fluid dynamics of sprinkler systems that included spray evaporation and distribution uniformity. At that time, the LEPA sprinkler method was being developed (ASAE, 1999), and all the information for this sprinkler method has been published during the past 20 years. Many developments and improvements in spray heads and pressure regulators for the spray method have occurred during these two decades.

LEPA irrigation is defined as: a low pressure irrigation method for uniformly applying small frequent irrigations at or near ground level to individual furrows (usually alternate furrows) with a mechanical-move system accompanied by soil tillage methods or tillage plus crop residue management to increase furrow surface water storage capacity (ASAE, 1999). Lyle and Bordovsky (1979, 1981) developed the LEPA sprinkler concept and conducted the first system evaluations (Lyle and Bordovsky, 1983). LEPA sprinkler devices soon became commercially available, and the LEPA method was evaluated on-farm by Fipps and New (1990). LEPA is used on-farm with small diameter bubblers located about 0.3 m above the ground and with socks or sleeves discharging water directly into furrows (Fipps and New, 1990).

Spray irrigation is defined as: the application of water by a small spray or mist to the soil surface, where travel through the air becomes instrumental in the distribution of water (ASAE, 1995). Spray irrigation was developed to reduce the droplet evaporation and drift inherent with impact sprinklers. The first spray devices were adaptions of chemical spray nozzles, but sprinkler equipment manufacturers soon developed irrigation spray heads. Today, many combinations of pressure regulators and spray heads, nozzles, and deflector plates are commercially available for the sprinkler designer.

EVALUATING SPRINKLER EFFICIENCY AND UNIFORMITY

Application efficiency, AE, and the uniformity coefficient, C_u, are two accepted methods for evaluating sprinkler performance. Burt et al. (1997) define application efficiency as:

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The author is **Arland D. Schneider**, ***ASAE Member Engineer***, Agricultural Engineer, USDA-ARS, PO Drawer 10, Bushland, TX 79012-0010, phone: 806.356.5732, fax: 806.356.5750, e-mail: <aschneid@ag.gov>.

$$AE = \frac{\text{Average depth of irrigation water contributing to a target}}{\text{Average depth of irrigation water applied}} \times 100 \quad (1)$$

An earlier AE definition (ASAE, 1995; ASCE, 1978) considers only the fraction of applied water stored in the root zone and potentially available for evapotranspiration:

$$AE = \frac{\text{Average depth of water stored in the root zone}}{\text{Average depth of irrigation water applied}} \times 100 \quad (2)$$

The main difference between the two definitions is the allowance for multiple beneficial uses in equation 1 and a single beneficial use in equation 2. Among the spray water loss pathways listed in table 1, droplet and canopy evaporation can beneficially contribute to evapotranspiration, and deep percolation can be beneficial for leaching salts. When collectors are used to measure sprinkler depth, beneficial use implicitly includes water that would be stored in the root zone and evaporated from the crop canopy. Droplet evaporation that might reduce evapotranspiration is considered a loss, and runoff and deep percolation are assumed to be zero. When using equations 1 and 2 to evaluate center pivots, individual irrigation depths are weighted in proportion to the area represented by the measurement.

Sprinkler uniformity will be described using Christiansen's Uniformity Coefficient, C_u, (Christiansen, 1942) for lateral move irrigation systems and Heermann and Hein's Uniformity Coefficient, U_{HH}, (Heermann and Hein, 1968) for center pivot irrigation systems. Christiansen (1942) defined C_u , (expressed as a decimal fraction) as:

$$C_u = 1.0 - \frac{\sum x}{mn} \quad (3)$$

where

m = the mean of n observations

x = deviation of individual observations from the mean value, m

With C_u known and assuming a normal population distribution, the lower one-quarter Distribution Uniformity (DU) can be calculated from the equation, DU = −0.591 + 1.59C_u (Warrick, 1983).

For U_{HH}, the sprinkler catch measurements are weighted in accordance with the area represented by the individual measurement. Heermann and Hein (1968) defined U_{HH} as:

$$U_{HH} = 1 - \frac{\sum_S S_S \left| D_S - \frac{\sum_S D_S S_S}{\sum_S S_S} \right|}{\sum_S D_S S_S} \quad (4)$$

where

D_S = total depth of application from a sprinkler system at a distance, S_S, from the center of rotation

S_S = distance from the center of rotation to the point where D_S is measured

Various methods are used to measure or calculate the depth of water applied by sprinkler devices on mechanical move irrigation systems. Collectors, the most common method, vary from small cans, approximately 100 mm in diameter, to large pans and troughs for collecting the discharge from LEPA devices. Weighing lysimeters with areas as large as several square meters can also be used as collectors (Schneider and Howell, 1990). The increase in the concentration of chemical tracers is a method for measuring air evaporation and drift. (Kohl et al., 1987; Kraus, 1966; Yazar, 1984). Individual LEPA nozzle discharges can be measured and used to calculate the depth of application along the irrigation system mainline (Lyle and Bordovsky, 1981; Buchleiter, 1992).

Sprinkler Water Loss Pathways

The water loss pathways proposed by Kraus (1966) are listed in table 1 for the LEPA and spray sprinkler methods. Although deep percolation is considered negligible for both sprinkler methods, small amounts of deep percolation must be balanced against small amounts of deficit irrigation even for the most uniform on-farm systems. For LEPA with runoff eliminated, the only water loss pathway is

Table 1. Water loss pathways of the LEPA and spray sprinkler methods and tillage options for reducing runoff

Water Loss Pathway	LEPA Sock	LEPA Bubble	Spray
Droplet evaporation	None	None	Some
Droplet drift	None	None	Possible
Canopy evaporation	None	None	Function of wetted diameter
Impounded water evaporation	Yes	Yes	Minimal
Wetted soil evaporation	1/3 to 1/2 of area	1/3 to 1/2 of area	Entire area
Surface movement from point	Possible	Probable	Possible
Surface movement to point	Possible	Probable	Possible
Field runoff	Possible	Possible	Possible
Deep percolation	Not likely	Not likely	Not likely
Tillage Option	**LEPA Sock**	**LEPA Bubble**	**Spray**
Basin tillage	Effective	Less effective	Very effective
Reservoir tillage	Somewhat effective	Somewhat effective	Effective
No-till	Not possible	Not possible	Possible
Ridge till	Possible	Possible	Possible

evaporation from ponded water during and after an irrigation. Spray irrigation is subject to droplet evaporation and drift in the air, evaporation from the crop canopy, and runoff and evaporation from the soil.

Droplet Evaporation and Drift

Droplet evaporation for spray irrigation is bounded by the energy available for transforming water from the liquid to the vapor phase and is estimated in the 1 to 2% range (Christiansen, 1937; Thompson et al., 1997). Kohl et al. (1987) measured spray evaporation losses ranging from 0.5 to 1.4% for smooth spray plates and 0.4 to 0.6% for coarse serrated spray plates. Drift from spray irrigation is more difficult to quantify because of the multiple factors affecting droplet size and the varying wind speed. This water loss can be reduced with low nozzle pressures and serrated spray plates having flat or convex shapes (Kohl, 1987).

Canopy Evaporation

Frost and Schwalen (1960) found that evapotranspiration losses with or without sprinkling were equal for well-watered, low-growing crops completely covering the soil and at low wind velocities. McMillan and Burgy (1960) showed that, "no appreciable differences were observed between evapotranspiration from wetted and unwetted vigorous grass covers." Neither of these researchers was able to quantify the difference between net and gross canopy evaporation.

More recently, other researchers have used more sophisticated techniques to quantify net interception losses during sprinkler irrigation (table 2). For example, McNaughton (1981) used the micrometeorological theory of advection to model interception losses contingent on sprinkler irrigation. With normal meteorological values substituted into his model, net losses were only a small fraction of applied water—usually much less than 10%. In an alternate approach, Tolk et al. (1995) measured transpiration with heat-balance sap flow gages to partition the net interception loss from the gross interception loss. Transpiration suppression due to evaporation of canopy intercepted water and microclimate modification resulted in net interception losses between 5.1 and 7.9% of applied water. Similar values were obtained by Thompson et al. (1997) who used the Cupid-DPE model to partition water losses during spray irrigation with a lateral move irrigation system. With a full corn canopy, they estimated the net interception loss to be 2.4%.

Runoff and Surface Storage

Most sprinkler runoff studies are comparisons of conventional tillage with basin or reservoir tillage or crop residue management. Table 1 lists tillage options for reducing runoff from high intensity sprinkler irrigation and their applicability to LEPA and spray irrigation. Basin tillage is the process of constructing dams or dikes in furrows to create surface storage basins (Lyle and Dixon, 1977). Initially used to store rainfall for dry-farmed crops, basin tillage was first used by Aarstad and Miller (1977) to prevent runoff with impact sprinkler irrigation of slopes up to 7%. With basin tillage of a 0.3% slope clay loam soil, Howell et al. (1995) reported a rainfall storage volume of nearly 50 mm and little runoff from LEPA irrigations of up to 25 mm depth for corn. Runoff due to LEPA and spray irrigation of diked (basin tillage) and undiked furrows was measured from 20-m-long plots of Pullman clay loam, a slowly permeable soil (Schneider and Howell, 1999b). With irrigation for 100% soil water replenishment, the percentages of seasonal irrigation lost to runoff with and without furrow diking were 0% and 12% for the spray method and 22% and 52% for the LEPA method. In evaluating a LEPA equipped center pivot irrigation system with circular ridge-tilled rows, Buchleiter (1992) measured runoff amounts of 30% of applied water from a 3% slope and 55% from an 8% slope.

Reservoir tillage consists of a subsoiler or chisel shank pulled at a depth of about 0.3 m followed by a paddle wheel which penetrates to the depth of the shank to form pits with small dikes between the pits (Longley, 1984; Coelho et al., 1996). Coelho et al. (1996) reported a reservoir tillage storage volume of about 20 to 22 mm that increased slightly during the year. The corresponding storage volume for alternate furrow LEPA irrigation would be 10 to 11 mm. Kincaid et al. (1990) evaluated conventional and reservoir tillage with spray irrigation of silty loam and sandy soils having slopes ranging from nearly level to 12%. With reservoir tillage, crop yields were generally larger, and in most cases, soil water content was slightly higher later in the season. Reservoir tillage prevented most runoff, which was as high as 43% on conventionally tilled plots.

Crop residues provide detention storage of sprinkler applied water, but the capacity is difficult to quantify and decreases as residue decays. Oliveira et al. (1987) found a high residue rate of 5.7 Mg/ha more effective than reservoir tillage for reducing runoff from a silt loam soil with a 1% slope.

Kranz and Eisenhauer (1990) and Sprugeon et al. (1995) compared conventional, basin and reservoir tillage and subsoiling on silty loam soils. For a 50 mm irrigation applied with a rainfall simulator on a 10% slope, Kranz and Eisenhauer (1990) measured runoff percentages of 24.8, 11.8, 7.8, and 40.8% with conventional, basin and reservoir tillage and subsoiling, respectively. With a slope of 1%, runoff amounts were nearly identical at 5.2, 5.4, and 5.8%, respectively, for conventional and reservoir tillage and subsoiling (no basin tillage treatment). Sprugeon et al. (1995) evaluated the same tillage methods with full-season LEPA bubble and flat (in-canopy) spray irrigation of corn on slopes ranging up to 3.9%. Reservoir tillage was more effective than basin tillage in maintaining soil water content and grain yields. For the LEPA and spray irrigation, their predicted decreases in grain yield per 1% increase in slope were 1.46 and 0.71 Mg/ha with conventional tillage and 0.90 and 0.16 Mg/ha with reservoir tillage.

Table 2. Published studies of net canopy evaporation

Investigator	Year	Measurement Technique	Gross Canopy Evaporation (%)	Net Canopy Evaporation (%)
McNaughton	1981	Advection theory model		≤ 10
Tolk et al.	1995	Weighing lysimeters and heat sap flow gages	10.7	5.6
Thompson et al.	1997	Energy balance model		2.4

Application Efficiency

LEPA Irrigation

Published studies of application efficiency for LEPA sprinkler devices are summarized in table 3. Lyle and Bordovsky (1981) initially calculated application efficiencies exceeding 99% by measuring the evaporation loss of water ponded in microbasins following LEPA irrigation. They estimated that less than 1% of the applied water was lost to evaporation during the 30 to 45 min that a free water surface remained in the basins. In a subsequent study, Lyle and Bordovsky (1983) subtracted losses due to both evaporation from the ponded water and surface runoff. Application efficiency then ranged from 96 to 100% with microbasins that ponded all applied water for infiltration and from 80 to 100% with open furrows that allowed surface runoff. Schneider and Howell (1990) measured application efficiencies ranging from 93 to 100% with 9-m^2 weighing lysimeters. The 3-m lysimeter length was similar to the furrow dike spacing in the field, and all sprinkled water was retained on the lysimeters. They defined application efficiency as the percent of applied water recorded by the weighing lysimeter. Howell et al. (1991) evaluated the sprinkler water loss components and considered the only significant water loss to be evaporation from the water ponded in basins after irrigation. They estimated the application efficiency for LEPA of corn with a full canopy to be 98%.

Spray Irrigation

Published studies of application efficiency and evaporation losses for spray irrigation are summarized in table 4. Study conditions were much more variable than for LEPA with various spray heads, spray plates, and spray head heights. In addition, droplet evaporation and drift and crop canopy evaporation vary with local weather conditions, but they have no affect LEPA application efficiency. As a result, the range of application efficiency for spray irrigation is larger than for LEPA irrigation. In-canopy spray or low elevation spray application (LESA) will have application efficiencies lying between those of LEPA and above canopy spray. Droplet evaporation is reduced and drift loss is essentially eliminated. Crop canopy evaporation will continue to occur if all or part of the canopy is wetted by spray heads being pulled through the crop. Field studies by Schneider and Howell (1999b) show nearly equal grain yields with equal amounts of irrigation by the above-canopy and in-canopy spray methods. Spray application efficiencies will be grouped by those using cans to measure irrigation depth and those using other methods.

Marek and Clark (1981) utilized 49-mm-diameter funnels draining into plastic bottles to make multiple sprinkler catches from center pivot irrigation systems at Bushland and Etter, Texas. Application efficiency along the 131-m-long Bushland system ranged from 60 to 117% and

Table 3. Published studies of application efficiency of LEPA sprinkler devices

Investigators	Year	Evaporation Definition	LEPA Device	LEPA Type	Evaporation Range (%)	Application Efficiency Range (%)
Lyle & Bordovsky	1981	Subtract evaporation of water ponded in basins	Locally fabricated drop tube and outlet	Bubble	≤ 1	≥ 99
Lyle & Bordovsky	1983	Subtract evaporation of water ponded in basins	Locally fabricateddrop tube and outlet	Bubble		96-100
Lyle & Bordovsky	1983	Subtract evaporation of ponded water and run-off from open furrows	Locally fabricated drop tube and outlet	Bubble		80-100
Schneider & Howell	1990	Increase in lysimeter mass	Rainbird	Bubble		93-100
Howell et al.	1991	Calculated from evaporation components	Not applicable	Not applic.		98

Table 4. Published studies of application efficiency or evaporation by spray sprinkler devices

Investigators	Year	Evaporation Definition	Spray Device	Type Spray Plate	Evaporation (%)	Applic. Effic. Range (%)	Applic. Effic. Avg (%)
Marek and Clark	1981	Sharp-edged 49-mm diam. funnel draining into bottle	Senninger Pivot Master 180° Rainbird 8×180°	Not specified Not specified		60-117 40-110	89 85
Howell and Phene	1983	Rain gage (40 mm diam.)	Nelson Spray I	Not specified	≈10	≈90	
Undersander et al.	1985	Sharp-edged 49-mm diam. funnel draining into bottle	Senninger Pivot Master 180° Rainbird 8×180°	Not specified Not specified		61-69 78-82	
Kincaid et al.	1986	0.1 × 2.44-m plastic catch trough	Nelson Spray I	Smooth, concave		95-100	0.984*
Kohl et al.	1987	Increase in potassium ion concentration	Nelson Spray I	Smooth, coarse, serrated	0.5-1.4 0.4-0.6		
Musick et al.	1988	Catch (oil) can	Not specified	Not specified		80-90	85
Schneider and Howell	1990	Increase in lysimeter weight	Senninger Super Spray	Serrated, medium, flat		92-104	101
Howell et al.	1991	Calculated from evaporation components	Not applicable	Not applicable		92	
Kincaid	1994	0.1 × 2.44-m plastic catch trough	Nelson Spray I	Smooth Smooth		90-117 81-110	100† 95*
Thompson et al.	1997	Energy balance model	Senninger Super Spray	Serrated, medium, flat	≤ 1		

* 2-m spray nozzle height.
† 1-m spray nozzle height.

averaged 89%. For the 160-m-long Etter system, the application efficiency ranged from 40 to 110% and averaged 85%. Undersander et al. (1985) utilized the same two center pivot systems to measure application efficiency during a multi-year cropping study with corn and grain sorghum. For the Bushland system, the average yearly application efficiencies measured during irrigation of two corn and sorghum crops were 61 and 69%. For the Etter system, the average yearly application efficiencies measured over three years with the same crops were 80, 82, and 78%. Musick et al. (1988) summarized application efficiency measurements made with oil cans for 100 center pivot irrigation systems in the Texas High Plains. Application efficiency increased from 80% with wind speeds exceeding 4.8 m/s to 85% for wind speeds ranging from 2.9 to 4.8 m/s to 90% for wind speed less than 2.4 m/s. Average application efficiency of the 100 center pivot irrigation systems was 85%. The application efficiency of low elevation spray heads measured by Howell and Phene (1983) with 40-mm-diameter rain gages was approximately 90%.

When techniques other than cans are used to measure spray water loss, evaporation is less than 10% and application efficiency exceeds 90%. Kohl et al. (1987) estimated spray evaporation losses by measuring the increase in the potassium ion concentration in the water. Evaporation losses ranged from 0.5 to 1.4% with smooth spray plates and from 0.4 to 0.6% with coarse, serrated spray plates. Schneider and Howell (1990) measured spray application efficiency as the percent of applied water recorded by weighing lysimeters similar to the measurements for LEPA irrigation. Their application efficiencies during irrigation of grain sorghum ranged from 92 to 104% and averaged 101%. Application efficiencies exceeding 100% were believed to be due to more water being intercepted by plants on the lysimeters than by plants adjacent to the lysimeters. When Howell et al. (1991) calculated application efficiency from the evaporation loss components, they estimated the application efficiency to be 92% for spray irrigation of corn with a full crop canopy. Kincaid et al. (1986) and Kincaid (1994) measured irrigation depth with 0.1 by 2.44 m troughs cut from 150-mm polyvinyl chloride pipe. For one lateral move and four center pivot systems, on farm application efficiencies for spray heads at a 2.0 m height ranged from 95 to 100% and averaged 98% (Kincaid et al., 1986). For a single lateral move system, application efficiency averaged 95% with a 2.4-m spray height and 100% with a 1.2-m spray height. Another recent approach to estimating spray evaporation losses is through the use of energy balance modeling (Thompson et al., 1997). Their estimate of spray droplet evaporation loss was less than 1% for corn with a full canopy.

Uniformity

LEPA Irrigation

Published uniformity coefficients for LEPA irrigation range from less than 0.1 to more than 0.9 (table 5). Variables causing the large range in uniformities are the direction of measurement, the location along the system mainline, the start and stop movement of the irrigation system and the length of catch basin used to calculate the uniformity. Most reported uniformity data are from lateral move irrigation systems rather than from the more common on-farm center pivot irrigation systems. Lyle and Bordovsky (1981) reported uniformity coefficients ranging from 0.94 to 0.97 based on nozzle discharge measurements from each drop tube along the irrigation system mainline. Hanson et al. (1988) calculated LEPA uniformity coefficients from measured tower movements of a lateral move irrigation system and the measured discharge from the application devices. Calculated uniformity coefficients in the direction of travel ranged from 0.69 to 0.80 in the interior of the lateral move irrigation system and from 0.78 to 0.82 at the end of the system.

When the uniformity of LEPA irrigation is measured in the direction of travel of the irrigation system with collectors less than 1.0 m long, uniformity coefficients tends to be quite small. The small uniformity coefficients result from the small irrigation depths while the system is moving and the large irrigation depths while it is stopped. For example, Fangmeier et al. (1990) measured the uniformity of a lateral move and a center pivot irrigation system with 0.35-m-long pans. Uniformity coefficients ranged from 0.39 to 0.87 for the lateral move system and from 0.33 to 0.96 for the center pivot system. For both systems, the uniformity was better for the end spans where the towers followed the setting of the percent timer. In the interior of the systems, tower movement was random with longer moving and stopped times. Buchleiter (1992) measured similar low uniformities in the direction of travel of a center pivot irrigation system with 0.1-m-long × 1-row-wide troughs. Near the fifth of eight towers of the

Table 5. Published studies of the uniformity of LEPA sprinkler devices

Investigators	Year	Measurement Technique	Uniformity Definition	Direction*	System and Location†	Uniformity or Range
Lyle & Bordovsky	1981	Timed volumetric catchments	Christiansen	A	L (System)	0.94-0.97
Hanson et al.	1988	Catch in 1 to 15 m check spacings calculated from measured tower speeds and nozzle discharges	Christiansen	T	L (5 of 8)	0.69-0.80
			Christiansen	T	L (8 of 8)	0.78-0.82
Fangmeier et al.	1990	Catch in 0.35-m-long pans	Christiansen	T	L (System)	0.39-0.87
		"	Christiansen	T	P (System)	0.33-0.96
Buchleiter	1992	Discharge of LEPA devices	Heermann & Hein	A	P (System)	0.96
		Catch in 0.1-m-long troughs	Christiansen	T	P (4 of 8)	0.42-0.72
		"	Christiansen	T	P (5 of 8)	0.09-0.42
		"	Christiansen	T	P (8 of 8)	0.89-0.96

* A indicates along the mainline, and T indicates in the direction of travel.

† (L) or (P) designates linear or center pivot system. The numbers designate the tower number for the measurement and the end tower number. System designates the entire system.

system, the uniformity coefficient ranged from 0.09 to 0.42. Uniformity coefficients increased to the 0.89 to 0.96 range near the outer or eight tower of the system. The low uniformities in the direction of travel occurred even though the LEPA devices had a measured uniformity coefficient of 0.96 along the system mainline.

The inherent low uniformity of LEPA irrigation can be increased with appropriately spaced basin checks and a finely adjusted irrigation system. For water that was non-uniformly applied to furrow lengths less than 1 m, Hanson et al. (1988) showed that the uniformity could be increased to about 0.82 with a check spacing of 3 to 4 m. This spacing was the best compromise between nonuniformity of the LEPA discharge and nonuniformity caused by the spatial variability of soil infiltration. Similarly, Fangmeier et al. (1990) found a check spacing of 2 m or more necessary to obtain a uniformity coefficient larger than 0.80. They also found that uniformity could be increased by reducing the alignment angles between the irrigation system spans from 0.7° to 0.4° to 0.25°.

Spray Irrigation

Published studies of the uniformity of spray sprinkler devices are listed in table 6. Marek and Clark (1981) made multiple catch can measurements from spray heads along the system mainline of two, short, center pivot irrigations systems. Uniformity coefficients from seven tests of a 131-m-long system ranged from 0.71 to 0.85 and averaged 0.81. For the other system, which was 160-m-long, uniformity coefficients from 12 tests ranged from 0.70 to 0.86 and averaged 0.79. Musick et al. (1988) reported distribution uniformities for 100 on-farm center pivot evaluations by the USDA Natural Resource Conservation Service. The uniformities were calculated from collector (oil can) measurements along the mainline of the center pivot systems. The reported distribution uniformities were converted to uniformity coefficients using the procedure of Warrick (1983) and are listed in table 6. Uniformity coefficients averaged 0.85, 0.80, and 0.79 for wind speed ranges of 0 to 2.4, 2.4 to 4.8, and ≥ 4.8 m/s. Hanson et al. (1986) used 78-mm-diameter catch cans to measure the uniformity of spray heads on a lateral move and a center pivot irrigation system. The uniformity coefficients along the lateral move and center pivot systems mainlines were 0.73 and 0.77, respectively. In the direction of travel of the lateral move system, the uniformity coefficient was 0.75 at the fifth of nine towers and 0.89 at the ninth or end tower. Similar uniformity coefficients for the center pivot system were 0.76 at the fifth of 10 towers and 0.90 at the tenth or end tower. Howell and Phene (1983) measured the uniformity of spray heads on one span of a laser-guided lateral move irrigation system. Uniformity coefficients were 0.82 along the span and 0.90 in the direction of travel. Kincaid et al. (1986) measured the uniformity of 20-m-long segments along the mainline of on farm center pivots and a lateral move system. For spray heights of 1.8 to 4.3 m, uniformity coefficients were in the narrow range of 0.92 to 0.95, but the 20 m segments may not have bee representative of the entire sprinkler system.

Discussion

The reported application efficiency of spray irrigation depends on the technique used to measure the depth of irrigation from the sprinkler device. Catches with small collectors are confounded by unknown evaporation loss from the collector and reduced catch as the wind speed increases. Kohl (1972) compared several commonly used collectors with a specially designed separatory funnel precipitation gage designed to reduce splash out and collector evaporation. For day time sprinkling, the catch in commonly used precipitation gages was generally only 50 to 80% of the catch in the separatory funnel. Kohl (1972) concluded that, "most of the evaporation loss charged against sprinkler irrigation should probably be charged against the catch unit itself." Marek et al. (1985) compared the separatory funnel with oil cans and a sharp-edged funnel and also concluded that the separatory funnel was superior. Livingston et al. (1985) showed that the percent catch of typically sized sprinkler collectors decreased to as low as 80% due to wind alone over the 3.3 to 6.2 m/s wind speed range. Very likely, much of the reduction in application efficiency with wind speed reported by Musick et al. (1988) was due to the collector and not to an actual reduction in sprayed water reaching the ground surface. Because of inherent errors with small collector

Table 6. Published studies of the uniformity of spray sprinkler devices

Investigators	Year	Measurement Technique	Uniformity Definition	Direction*	System and Location†	Uniformity or Range
Marek and Clark	1981	Sharp-edged, 49-mm diam. funnel draining into bottle	Heermann & Hein	A	P (System)	0.71-0.85
			Heermann & Hein	A	P (System)	0.70-0.86
Howell and Phene	1983	Rain gage (40-mm diam.)	Christiansen	A	L (Span)	0.82
				T	L (Nozzle)	0.90
Hanson et al.	1986	Catch cans (78-mm diam.)	Christiansen	A	L (System)	0.73
			Christiansen	T	L (5 of 9)	0.75
			Christiansen	T	L (9 of 9)	0.89
			Heermann & Hein	A	P (System)	0.77
			Heermann & Hein	T	P (5 of 10)	0.76
			Heermann & Hein	T	P (10 of 10)	0.90
Kincaid et al.	1986	Metal cans (150-mm diam.)	Christiansen	A	P & L (20-m long test section)	0.92-0.95
Musick et al.	1988	Catch cans (oil cans)	Heermann & Hein	A	P (System)	0.79-0.85

* A indicates along the mainline, and T indicates in the direction of travel.

† (L) or (P) designates linear or center pivot system. The numbers designate the tower number for the measurement and the end tower number. System designates the entire system.

measurements, the author recommends that other methods be used for measuring the application efficiency of spray irrigation.

For both the LEPA and spray sprinkler methods, droplet evaporation has less effect on irrigation efficiency than drift, surface runoff, or non-uniformity. Droplet evaporation is bounded by the energy available for evaporation and will be negligible with LEPA and only a few percent with spray (Christiansen, 1937, 1942; Thompson et al., 1997). On the other hand, drift and runoff losses are not bounded, and the theoretical upper limit is 100% of the applied water. Drift and runoff are spatially variable and reduce the uniformity as well as the application efficiency.

Accumulative LEPA and spray irrigations would be expected to be more uniform than the individual irrigations, but data are not available to verify this assumption. Pair (1968) presented individual and accumulative uniformity coefficients for five irrigations with a handmove impact sprinkler system. For 11 plot areas, the average uniformity coefficients for the five individual irrigations ranged from 0.69 to 0.77, but the accumulative uniformity coefficients ranged from 0.85 to 0.92. A similar increase would increase the accumulative uniformity coefficient for well-designed LEPA and spray systems above 0.90.

Even though LEPA and spray are both highly efficient sprinkler methods, selection of the most efficient system requires careful evaluation of the water loss pathways in table 1. LEPA is the most efficient sprinkler method available, but it would be an inefficient design choice in an application where runoff approaches 50% as measured on-farm by Buchleiter (1992) or from research plots by Schneider and Howell (1999). The spray sprinkler method would be a poor design choice for preseason irrigation where soil evaporation within 24 h after irrigating can be as large as 10 mm (Unpublished data, J. A. Tolk, USDA-ARS, Bushland, Texas). In both of these examples, misuse of a sprinkler method with a potential application efficiency exceeding 90% might result in half of the sprinkler applied water being lost to non-beneficial use within one day after irrigating.

Conclusions

With negligible runoff and deep percolation, reported application efficiencies are in the 95 to 98% range for the LEPA sprinkler method and exceed 90% for the spray sprinkler method. Runoff control is always required to achieve high application efficiency with LEPA and is often necessary for high efficiency with spray. Uniformity coefficients for LEPA will be larger than for spray along the irrigation system mainline and are likely to be smaller in the direction of travel. Along the mainline, reported uniformity coefficients are generally in the 0.94 to 0.97 range for LEPA and in the 0.75 to 0.85 range for spray. In the direction of travel, uniformity coefficients tend to be larger near the ends of a mechanical move irrigation system and smaller in the interior of the system. They generally lie in the 0.75 to 0.85 range for LEPA with furrow diking and in the 0.75 to 0.90 range for spray. Furrow diking on a 2 to 4 m spacing is critical for LEPA uniformity on start and stop irrigation systems because the LEPA applications during several unequal start and stop times are averaged.

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