DROPLET KINETIC ENERGY OF MOVING SPRAY-PLATE CENTER-PIVOT IRRIGATION SPRINKLERS

B. A. King, D. L. Bjorneberg

ABSTRACT. *The kinetic energy of discrete water drops impacting a bare soil surface generally leads to a drastic reduction in water infiltration rate due to formation of a seal on the soil surface. Under center-pivot sprinkler irrigation, kinetic energy transferred to the soil prior to crop canopy development can have a substantial effect on seasonal runoff and soil erosion, especially when the soil is not protected by crop residue cover. Droplet kinetic energy of seven commercial off-center action rotating spray-plate sprinklers was characterized over a range of flow rates and pressures. Sprinkler droplet kinetic energy was characterized using two methods: droplet kinetic energy per unit sprinkler discharge, and droplet kinetic energy applied per unit water depth under center-pivot irrigation with 3 m sprinkler spacing. The two methods are correlated, but kinetic energy per unit sprinkler discharge does not represent droplet kinetic energy applied to the soil under center-pivot irrigation, as the correlation coefficient is not equal to 1. Droplet kinetic energy applied for a given flow rate and operating pressure varied by up to 200% among the sprinklers evaluated. Designing sprinklers that minimize the kinetic energy transferred to bare soil will require a monotonic decreasing application rate with radial distance, as any peak in application rate at large radial distances will result in a peak in specific power. Kinetic energy per unit drop volume will always increase with radial distance, as drops sizes get larger with radial distance. The sprinkler with the lowest droplet kinetic energy applied or the lowest average composite specific power may not necessarily be the sprinkler that results in the greatest infiltrated depth or the least potential runoff. Thus, droplet kinetic energy is not suitable as a single parameter to select between sprinkler choices.*

Keywords. *Center-pivot, Infiltration, Kinetic energy, Runoff, Sprinkler, Sprinkler irrigation.*

When discrete water drops impact a bare soil surface, a drastic reduction in water infiltration rate is generally observed due to formation of a seal on the soil surface. The decrease in water infiltration rate of soils under droplet impact was first investigated by Duley (1939), Borst and Woodburn (1942), and Ellison (1945). McIntyre (1958) was the first to measure the saturated hydraulic conductivity of soil surface seals created by raindrop impact. Seal saturated hydraulic conductivity was found to be two to three orders of magnitude less than that of the underlying soil. The physical processes involved in formation of a surface seal include compaction, aggregate destruction, soil particle detachment, dispersion, and deposition of fine particles in surface pores. These physical processes reduce surface soil porosity and mean pore size to create a disturbed layer with reduced hydraulic conductivity that expands in size and depth with time (Assouline and Mualem, 1997). The effect that soil surface seal formation has on water infiltration rate has been studied by Agassi et al. (1985, 1994), Thompson and James (1985), Mohammed and Kohl (1987), Ben-Hur et al. (1987), Betzalel et al. (1995), and Assouline and Maulem (1997). These studies have shown that the kinetic energy of discrete drops impacting a bare soil surface is a primary factor in determining the reduction in water infiltration rate due to soil surface seal formation. Much of the research on soil surface sealing has focused on rainfall conditions, but the same processes occur under sprinkler irrigation (von Bernuth and Gilley, 1985; Ben-Hur et al., 1995; DeBoer and Chu, 2001; Silva, 2006). Soil surface seal formation in combination with high water application rates under center-pivot sprinkler irrigation exacerbates potential runoff and erosion hazards. Runoff under center-pivot sprinkler irrigation is a well recognized problem (Undersander et al., 1985; DeBoer et al., 1992; Hasheminia, 1994; Ben-Hur et al., 1995; Silva, 2006, King and Bjorneberg, 2011), but it is normally unseen because runoff often infiltrates before exiting the field boundary, as only a small fraction of the field is irrigated (saturated) at a given time and/or runoff collects in low spots within the field.

The influence that droplet kinetic energy applied by center-pivot sprinklers has on infiltration, runoff, and erosion is well known in the center-pivot sprinkler irrigation indus-

Submitted for review in August 2011 as manuscript number SW 9316; approved for publication by the Soil & Water Division of ASABE in December 2011. Presented at the 5th Decennial Irrigation Symposium as Paper No. IRR108726.

Mention of trade names, proprietary products, or specific equipment does not constitute a guarantee or warranty by the authors or their institutions and does not imply approval of product to the exclusion of others that may be suitable.

The authors are Bradley A. King, ASABE Member, Research Agricultural Engineer, and David L. Bjorneberg, ASABE Member, Supervisory Research Agricultural Engineer, USDA-ARS Northwest Irrigation and Soils Research Laboratory, Kimberly, Idaho. Corresponding author: Bradley A. King, USDA-ARS NWISRL, 3793 N. 3600 E., Kimberly, ID 83341-5076; phone: 208-423-6501; fax: 208-423-6555; e-mail: brad.king@ ars.usda.gov.

try. Over the past two decades, center-pivot sprinkler manufacturers have continued to develop sprinklers that reduce peak water application rates and droplet kinetic energy to sustain infiltration rates and reduce runoff and erosion. Consequently, there are numerous sprinkler choices available to the center-pivot irrigation system designer and crop producer; however, limited quantitative information is available that relates these choices to performance with regard to infiltration, runoff, and erosion. King and Bjorneberg (2009, 2011) observed significant differences in runoff and erosion between sprinkler types even though the flow rates and wetted diameters were similar. Kincaid (1996) developed a model to estimate sprinkler droplet kinetic energy per unit discharge volume of common sprinkler types as a function of nozzle size and operating pressure for use as a design aid in selecting center-pivot sprinklers. DeBoer (2002) evaluated the kinetic energy per unit discharge of select moving spray-plate sprinklers for center-pivot irrigation systems and developed a model of kinetic energy as a function of spray-plate type, nozzle size, and operating pressure. King and Bjorneberg (2010) evaluated droplet kinetic energy applied to the soil by moving spray-plate sprinklers and found that sprinkler droplet kinetic energy per unit discharge does not represent actual droplet kinetic energy applied under center-pivot irrigation.

The objective of this study was to evaluate droplet kinetic energy applied and droplet kinetic energy per unit discharge of several common center-pivot sprinklers over a range of nozzle sizes and operating pressures, and evaluate the relationship between the two droplet kinetic energy measures. This study concentrates on center-pivot sprinklers that use "off-center" action to rotate the spray-plate, as this class of center-pivot sprinklers has not been previously studied.

METHODS AND MATERIALS

The sprinkler devices used in this study and corresponding operating pressures and nozzle sizes are listed in table 1. The I-Wob, Xi-Wob (Senninger Irrigation, Inc., Clermont, Fla.), N3000, and O3000 (Nelson Irrigation Corp., Walla Walla, Wash.) sprinklers use an off-center oscillating plate with grooves of equal geometry to break up the nozzle jet and create discrete water drops. The R3000 sprinklers (Nelson Irrigation Corp., Walla Walla, Wash.) use rotating plates with grooves to break up the nozzle jet and create discrete streams of water leaving the plate edge. The R3000 sprinkler with the brown plate has ten grooves with multiple trajectory angles and widths. The R3000 sprinkler with the red plate has six grooves of equal trajectory angle (12°) and width. The R3000 sprinklers have plate rotational speeds of 2 to 4 rpm. The S3000 sprinkler (Nelson Irrigation Corp., Walla Walla, Wash.) also uses a rotating plate with grooves to break up the nozzle jet. The purple rotating plate with six grooves of equal width and trajectories from 12° to 20° has a rotational speed of 400 to 500 rpm. Three flow rates were evaluated for each sprinkler: low (<10 L min^{-1}), medium (~20 L min^{-1}), and high (~45 L min^{-1}). Sprinkler nozzle sizes were selected to provide similar flow

Table 1. Sprinkler types, nozzle sizes, pressures, and flow rates used in study (flow rates based on manufacturer data).

Nozzle Diameter	Flow Rate (L min^{-1})		
(mm)	69 kPa	103 kPa	138 kPa
Senninger I-Wob: Black plate (9-groove standard angle), Blue plate (9-groove low angle), and White plate (6-groove low angle)			
3.57	6.9	8.2	9.5
5.56	16.6	19.8	22.8
7.94	33.1	39.5	45.6
Senninger I-Wob: Gray plate (6-groove low angle UP3 nozzle)			
3.57	6.9	8.3	9.7
5.56	16.7	20.5	23.7
7.94	34.1	41.8	48.3
Senninger Xi-Wob: Black plate (6-groove 15° trajectory), Blue plate (6-groove 10° trajectory), and Gray plate (9-groove 10° trajectory)			
3.57	6.9	8.2	--
5.56	16.6	19.8	--
7.94	33.1	39.5	--
Nelson N3000: Green plate (9-groove 21° trajectory) and Blue plate (7-groove 12° trajectory)			
3.77	7.5	9.1	--
5.75	17.5	21.4	--
8.14	35.5	43.4	--
Nelson O3000: Black plate (9-groove standard single trajectory)			
3.77	7.5	9.1	10.6
5.75	17.5	21.4	24.7
8.14	35.5	43.4	50.2
Nelson S3000: Purple plate (6-groove multi-trajectory)			
5.75	--	21.4	--
8.14	--	43.4	--
Nelson R3000: Red plate (6-groove 12° trajectory) and Brown plate (6-groove multi-trajectory)			
5.35	--	--	21.2
7.54	--	--	42.7

rates at the given operating pressures based on manufacturer data. Three operating pressures (69, 103, and 138 kPa) were evaluated for each sprinkler when within the manufacturer's recommended operating pressure. Some of the tests were below manufacturer's recommended design flow rates but were used regardless to maintain flow rate consistency across all sprinklers.

Drop sizes and velocities were measured using a Thies Clima Laser Precipitation Monitor (TCLPM, Adolf Thies GmbH & Co. KG, Gottingen, Germany) (King et al., 2010). Measurements were conducted indoors with no wind. Measurements were collected at 1 m increments radially outward from the sprinkler. A minimum of 10,000 drops were measured at each location except at the most distal radial location, where a minimum of 4,000 drops were measured to save time. Sprinklers were positioned on the end of a drop tube with the nozzle discharge directed vertically downward 0.8 m above the laser beam of the TCLPM. Pressure regulators with nominal pressure ratings for the test condition were used to control pressure at the base of the sprinkler. A pressure gauge located between the pressure regulator and sprinkler base was used to monitor pressure. Pressures were within ±7 kPa of the nominal pressure rating. Specific details of the experimental methods are provided by King et al. (2010).

Radial application rate distributions for the sprinklers were also measured indoors with no wind. Catch cans, 150 mm in diameter and 180 mm tall, spaced at 0.5 m increments from the sprinkler in one radial direction, were used to collect water. The sprinkler height was 0.8 m above can opening. The duration of each test was 30 to 60 min. Water collected in each can was measured using a graduated cylinder. Application rate was calculated based on the diameter of the catch cans and the duration of each test.

Kinetic energy per unit sprinkler discharge (area-weighted kinetic energy per unit drop volume), KE_d (J L^{-1}), was computed as (King and Bjorneberg, 2010):

$$KE_d = \frac{\sum_{i=1}^{R}\left(\frac{\sum_{j=1}^{ND_i}\frac{\rho_w \pi d_j^3 v_j^2}{12}}{1000\sum_{j=1}^{ND_i}\frac{\pi d_j^3}{6}}\right)A_i}{\sum_{i=1}^{R} A_i} \tag{1}$$

where R is the number of radial measurement locations, ND_i is the number of drops measured at the ith radial location, ρ_w is the mass density of water (kg m^{-3}), d_j is the measured diameter (m) of the jth drop, v_j is the measured velocity (m s^{-1}) of the jth drop, and A_i is the wetted area (m^2) associated with ith radial location. The wetted area was computed as $A_i = 2\pi S r_i$ where S is the radial distance (m) between adjacent radial measurement locations, and r_i is the radial distance (m) from the sprinkler to the ith measurement location. The resulting value represents the average kinetic energy per liter of drop volume applied over the wetted area.

Specific power, SP (W m^{-2}), is a function of the radial measurement location and was computed as (King and Bjorneberg, 2010):

$$SP_i = \left(\frac{\sum_{j=1}^{ND_i}\frac{\rho_w \pi d_j^3 v_j^2}{12}}{1000\sum_{j=1}^{ND_i}\frac{\pi d_j^3}{6}}\right)\cdot\frac{AR_i}{3600} \tag{2}$$

where AR_i is the average application rate (mm h^{-1}) associated with the ith radial location. SP represents the rate at which kinetic energy is transferred to the soil surface as a function of radial distance from the sprinkler. SP is sometimes referred to as droplet energy flux (Thompson and James, 1985). A sprinkler radial SP distribution is analogous to a sprinkler radial water application rate distribution. The depth of water applied by a center-pivot sprinkler irrigation system can be determined by integrating the composite overlapped sprinkler application rate perpendicular to the sprinkler lateral with respect to time. Similarly, the kinetic energy applied by a center-pivot irrigation system can be determined by integrating the composite overlapped sprinkler SP distribution perpendicular to the sprinkler lateral with respect to time.

A model written in Visual Basic was used to simulate the composite water application rate for a 0.3 m spaced square grid oriented perpendicular and parallel to the lateral. The composite application rate was computed by overlapping the radial water application rate distributions from successive sprinklers spaced at 3 m increments along the center-pivot lateral. An average composite application rate distribution perpendicular to the sprinkler lateral was computed as the average of simulated application rates over a 3 m distance parallel to the center-pivot lateral centered about a sprinkler. Sprinkler application rate distributions determined indoors were used in the simulation model. Sprinkler application rate distributions were interpolated to 0.3 m radial increments using cubic spline interpolation between catch can measurements.

Water application depth was determined by numerically integrating the average composite application rate distribution over time. The time required for the center-pivot lateral to pass over a location when applying 25 mm of water was determined by adjusting the integration period (center-pivot lateral travel speed). Average center-pivot application rate was calculated as the numerical average of the average composite application rate distribution perpendicular to the sprinkler lateral.

The composite center-pivot SP distribution perpendicular to the center-pivot lateral was computed by the simulation model as the sum of SP from sprinklers applying water to a fixed point on the soil as the center-pivot system travels over the fixed point. Sprinkler SP distributions (eq. 2) were interpolated to 0.3 m radial distance increments using cubic spline interpolation of the TCLPM measurements. An average composite SP distribution was calculated as the average of simulated SP over a 3 m distance parallel to the center-pivot lateral centered about a sprinkler. Average center-pivot SP was calculated as the numerical average of the average composite SP distribution perpendicular to the sprinkler lateral.

Total kinetic energy from an application of 25 mm of water was determined by numerically integrating the average composite SP distribution using the same integration period required to apply 25 mm of water. Total kinetic energy applied per unit volume of water, KE_a (J m^{-2} mm^{-1}), was determined by dividing the total kinetic energy by the depth of water applied (25 mm). Total kinetic energy per unit depth of water, with units of J m^{-2} mm^{-1}, is used because it is more intuitive than J L^{-1} and is numerically equivalent to kinetic energy per unit volume applied (J L^{-1}) (1 mm of water over 1 m^2 equals 1 L).

RESULTS AND DISCUSSION

Results from determination of KE_d and KE_a for the sprinklers used in the study are shown in table 2. Minimum and maximum KE_d values as influenced by sprinkler, flow rate, and pressure are summarized in table 3. Universally, the I-Wob sprinkler with the gray plate produced the minimum value of KE_d across all sprinklers tested. Kinetic energy per unit sprinkler discharge varied by up to 200% across the sprinklers tested. Minimum and maximum KE_a values as influenced by sprinkler, flow rate, and pressure are summarized in table 4. The I-Wob sprinkler with the gray plate was universally the lowest KE_a sprinkler tested. Droplet kinetic energy applied by a sprinkler varied by up to 200% within a flow rate-pressure category, the minimum

Table 2. Kinetic energy per unit sprinkler discharge (KE_d), applied kinetic energy per unit irrigation depth (KE_a), average composite specific power, and average composite water application rate computed by overlapping distributions from sprinklers spaced 3 m along the lateral.

Nozzle Size (mm)	Pressure (kPa)	KE_d (J L^{-1})	KE_a (J m^{-2} mm^{-1})	Specific Power (W m^{-2})	Application Rate (mm h^{-1})
Senninger I-Wob: Black plate 9-groove					
3.57	69	7.69	6.15	0.024	10.9
3.57	103	8.57	6.61	0.027	13.9
3.57	138	8.57	6.06	0.025	14.5
5.56	69	9.21	7.82	0.067	26.1
5.56	103	10.82	8.12	0.065	28.0
5.56	138	9.98	7.55	0.071	31.7
7.94	69	12.85	10.25	0.146	47.2
7.94	103	13.76	11.00	0.159	51.9
7.94	138	12.2	9.92	0.155	56.3
Senninger I-Wob: Blue plate 9-groove					
3.57	69	8.79	8.49	0.035	14.7
3.57	103	9.87	7.64	0.031	14.5
3.57	138	8.49	7.10	0.035	17.8
5.56	69	11.31	11.67	0.093	28.7
5.56	103	11.45	10.20	0.090	31.7
5.56	138	11.04	9.43	0.108	41.7
7.94	69	13.50	15.17	0.244	57.9
7.94	103	14.14	14.06	0.228	56.1
7.94	138	11.47	10.77	0.210	70.2
Senninger I-Wob: White plate 6-groove					
3.57	69	10.59	10.24	0.037	11.9
3.57	103	8.60	7.47	0.031	12.8
3.57	138	8.16	6.59	0.034	14.7
5.56	69	11.78	12.13	0.101	28.7
5.56	103	11.52	11.01	0.095	28.4
5.56	138	10.40	9.33	0.099	33.7
7.94	69	14.97	15.65	0.237	54.4
7.94	103	13.31	13.61	0.229	55.6
7.94	138	13.03	12.93	0.229	61.4
Senninger I-Wob: Gray plate 6-groove					
3.57	69	7.32	6.05	0.024	14.3
3.57	103	6.44	5.07	0.023	14.0
3.57	138	6.05	4.41	0.024	17.8
5.56	69	7.31	6.46	0.066	34.8
5.56	103	7.32	5.74	0.056	30.6
5.56	138	6.93	5.04	0.057	37.5
7.94	69	8.35	7.67	0.129	57.4
7.94	103	7.67	6.45	0.122	65.1
7.94	138	8.17	6.55	0.127	67.2
Senninger Xi-Wob: Gray plate 9-groove					
3.57	69	8.49	6.97	0.025	13.0
3.57	103	9.08	6.51	0.028	15.0
5.56	69	11.15	9.20	0.087	30.7
5.56	103	9.44	7.44	0.073	35.4
7.94	69	12.39	9.99	0.173	62.5
7.94	103	11.33	8.70	0.161	66.5
Senninger Xi-Wob: Black plate 6-groove					
3.57	69	9.01	8.14	0.030	13.3
3.57	103	7.51	6.47	0.026	14.7
5.56	69	11.27	9.41	0.074	28.2
5.56	103	9.77	7.49	0.076	30.1
7.94	69	12.25	10.39	0.150	50.6
7.94	103	11.98	8.60	0.130	54.3
Senninger Xi-Wob: Blue plate 6-groove					
3.57	69	7.56	6.92	0.029	14.9
3.57	103	9.25	6.87	0.029	13.5
5.56	69	13.36	9.66	0.082	30.7
5.56	103	9.11	7.37	0.074	34.6
7.94	69	12.29	9.64	0.163	60.8
7.94	103	11.44	8.17	0.149	62.9

KE_a was 46% to 59% of the maximum KE_a. The correlation between KE_d and KE_a is shown in figure 1. The linear regression is significant ($p < 0.001$) with an R^2 of 0.78, indicating that 78% of the variation in KE_a can be explained by KE_d. Note that kinetic energy per unit discharge (KE_d) is consistently greater than applied kinetic energy (KE_a). Kinetic energy per unit discharge does not accurately represent sprinkler selection choices, as the sprinklers with maximum KE_a are not necessarily the same as those with maximum KE_d (tables 3 and 4). Calculation of KE_d is strongly influenced by drop size because larger drops have greater kinetic energy and travel farther from the sprinkler, representing a larger portion of the wetted area (eq. 1).

In general, KE_d and KE_a both increase with nozzle size because drop sizes increase with flow rate (table 2). Both KE_d and KE_a generally decrease with pressure because drop sizes decrease with pressure. However, changes in the radial application profiles with flow rate can lead to exceptions, such as for the I-Wob black plate sprinkler at 103 kPa vs. 69 kPa (table 2).

Examining why the R3000 red and brown plate sprinklers with equal nozzle sizes and operating pressures have a 25% difference in kinetic energy per unit of water applied provides some insight into designing center-pivot sprinklers to produce less kinetic energy. The application rate patterns of these sprinklers are shown in figure 2. The R3000 sprinkler with the brown plate has approximately 1.3 m greater wetted radius than with the red plate. The peak application

Table 2 (continued). Kinetic energy per unit sprinkler discharge (KE_d), applied kinetic energy per unit irrigation depth (KE_a), average composite specific power, and average composite water application rate computed by overlapping distributions from sprinklers spaced 3 m along the lateral.

Nozzle Size (mm)	Pressure (kPa)	KE_d (J L^{-1})	KE_a (J m^{-2} mm^{-1})	Specific Power (W m^{-2})	Application Rate (mm h^{-1})
Nelson N3000: Green plate 9-groove					
3.77	69	10.98	10.61	0.035	11.8
3.77	103	10.13	8.40	0.030	12.4
5.75	69	10.17	9.45	0.070	26.5
5.75	103	11.40	9.35	0.078	30.2
8.14	69	12.91	11.09	0.156	50.7
8.14	103	13.47	9.98	0.168	60.7
Nelson N3000: Blue plate 7-groove					
3.77	69	9.21	8.22	0.035	13.6
3.77	103	7.37	6.20	0.030	16.5
5.75	69	10.91	9.79	0.084	31.0
5.75	103	10.90	8.80	0.082	32.2
8.14	69	14.24	12.14	0.202	60.0
8.14	103	12.69	10.58	0.230	74.4
Nelson O3000: Black plate 9-grove standard angle					
3.77	69	10.18	9.75	0.032	10.2
3.77	103	9.09	7.84	0.029	11.8
3.77	138	8.37	8.11	0.039	14.6
5.75	69	10.68	9.59	0.075	22.7
5.75	103	9.85	9.34	0.086	29.4
5.75	138	9.71	9.77	0.095	34.9
8.14	69	11.80	11.29	0.185	51.7
8.14	103	12.09	11.21	0.230	58.7
8.14	138	9.96	9.39	0.183	70.0
Nelson S3000: Purple plate 6-groove multi-trajectory					
5.75	103	11.17	9.75	0.076	28.4
8.14	103	12.17	10.94	0.188	61.7
Nelson R3000: Red plate 6 groove 12° trajectory					
5.35	138	10.06	9.05	0.071	28.2
7.54	138	13.31	12.15	0.175	51.0
Nelson R3000: Brown plate multi-trajectory					
5.35	138	12.06	9.39	0.069	29.1
7.54	138	13.46	9.75	0.129	47.6

Table 3. Sprinklers that have the maximum and minimum kinetic energy per unit sprinkler discharge (KE_d) in units of J L^{-1} as influenced by flow rate and operating pressure.

Pressure (kPa)	Flow Rate Range: Low	Medium	High
Minimum KE_d			
69	I-Wob Gray (7.32)	I-Wob Gray (7.31)	I-Wob Gray (8.35)
103	I-Wob Gray (6.44)	I-Wob Gray (7.32)	I-Wob Gray (7.67)
138	I-Wob Gray (6.05)	I-Wob Gray (6.93)	I-Wob Gray (8.17)
Maximum KE_d			
69	I-Wob White (10.59)	Xi-Wob Blue (13.36)	I-Wob White (14.97)
103	N3000 Green (10.13)	I-Wob White (11.52)	I-Wob Blue (14.14)
138	I-Wob Black (8.57)	R3000 Brown (12.06)	R3000 Brown (13.46)

Table 4. Sprinklers that have the maximum and minimum applied kinetic energy per unit irrigation depth (KE_a) in units of J m^{-2} mm^{-1} as influenced by flow rate and operating pressure.

Pressure (kPa)	Flow Rate Range: Low	Medium	High
Minimum KE_a			
69	I-Wob Gray (6.05)	I-Wob Gray (6.46)	I-Wob Gray (7.67)
103	I-Wob Gray (5.07)	I-Wob Gray (5.74)	I-Wob Gray (6.45)
138	I-Wob Gray (4.41)	I-Wob Gray (5.04)	I-Wob Gray (6.55)
Maximum KE_a			
69	N3000 Green (10.61)	I-Wob White (12.13)	I-Wob White (15.65)
103	N3000 Green (8.40)	I-Wob White (11.01)	I-Wob Blue (14.06)
138	O3000 Black (8.11)	O3000 Black (9.77)	R3000 Red (12.15)

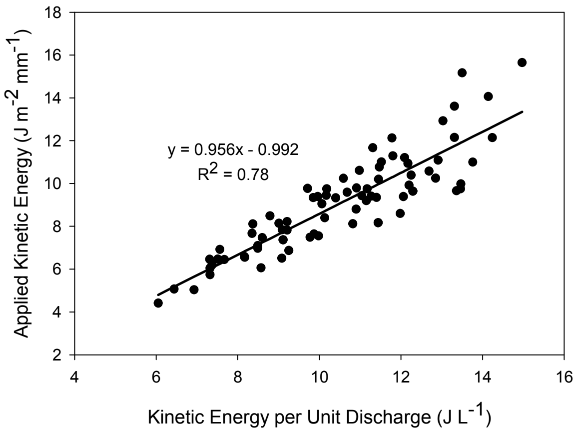

Figure 1. Linear correlation between kinetic energy per unit discharge (KE_d) and kinetic energy applied per unit depth of water application (KE_a) for sprinklers used in this study.

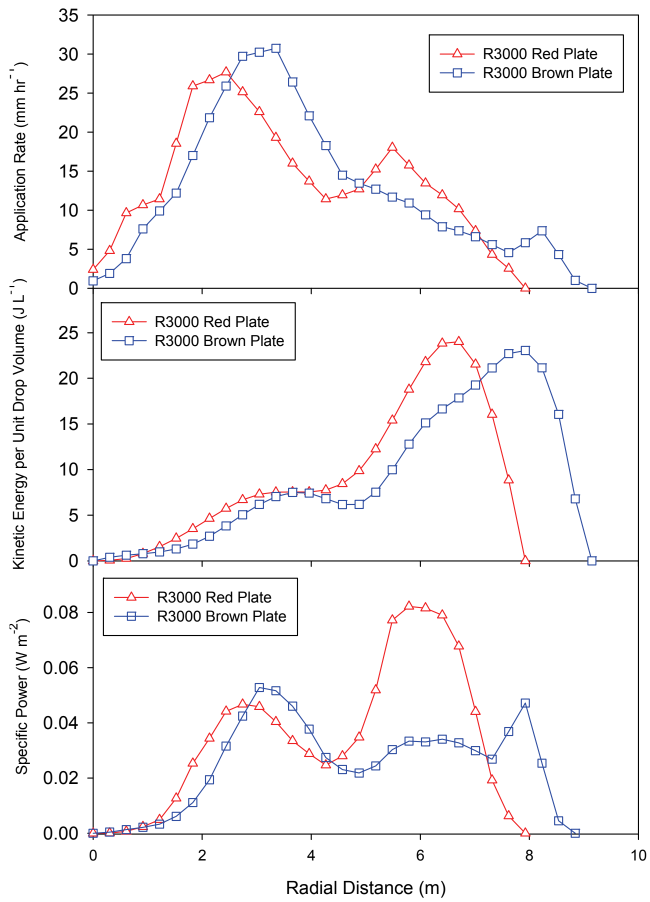

Figure 2. Values of application rate, kinetic energy per unit drop volume, and specific power as a function of distance from the R3000 red and brown plate sprinklers.

rate occurs at 2 to 3 m from the sprinkler for both plate combinations. The red plate produces a secondary peak at approximately 5.5 m from the sprinkler, while the brown plate has a much smaller secondary peak at approximately 8.5 m. Kinetic energy per unit drop volume as a function of distance from the sprinkler is similar for both sprinklers (fig. 2). Peak kinetic energy per unit drop volume is about equal for the two sprinklers, with the peak occurring at approximately 6.5 m for the red plate and at approximately 8 m for the brown plate. Kinetic energy per unit discharge (table 2) is slightly greater for the brown plate because it has a greater wetted radius, and kinetic energy per unit discharge is independent of application rate pattern (eq. 1). Specific power as a function of radial distance calculated by multiplying application rate and kinetic energy per unit drop volume (eq. 2) is vastly different for the two plate choices (fig. 2). The red plate has a peak specific power at approximately 6 m from the sprinkler that is approximately 65% greater than for the brown plate. When this higher peak specific power from several sprinklers is added (overlapped), the resulting kinetic energy applied is greater than for the brown plate sprinkler, with an equal water application depth.

One method of minimizing applied kinetic energy is to design a sprinkler with monotonically decreasing specific power with distance from the sprinkler. This will require a monotonically decreasing application rate with radial distance, as any peak in application rate at large radial distances will result in a peak in specific power. Kinetic energy per unit drop volume will always increase with radial distance, as drops size increases with radial distance.

Average composite water application rate and average composite specific power computed using the sprinkler overlap simulation program for sprinklers spaced 3 m along

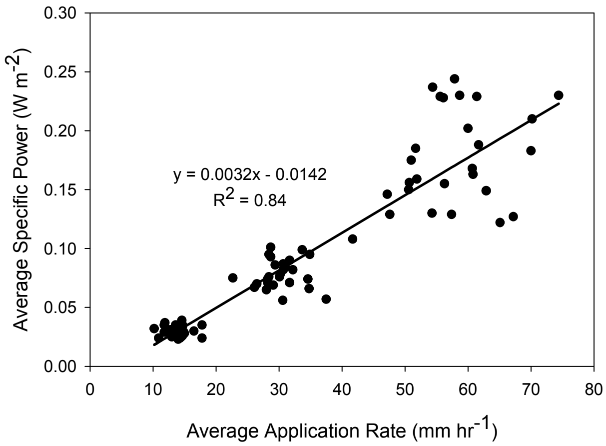

Figure 3. Linear correlation between average composite application rate and average composite specific power calculated using the simulation model for sprinklers used in this study spaced 3 m along the lateral.

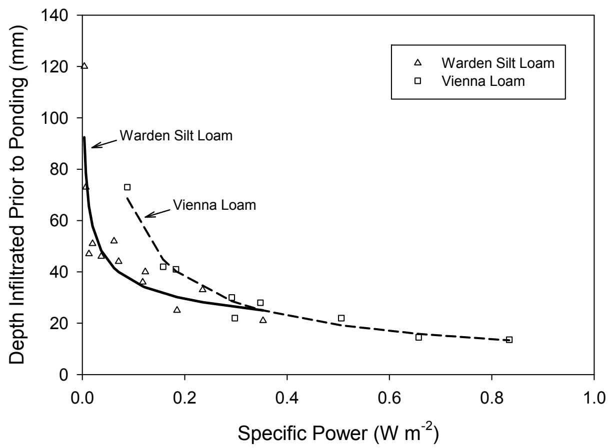

Figure 4. Effect of specific power on depth of water infiltrated prior to ponding for a Warden silt loam soil (Thompson and James, 1985) and Vienna loam soil (Mohammed and Kohl, 1987).

a lateral are given in table 2. The correlation between average composite application rate and average composite specific power is shown in figure 3. The linear regression is significant ($p < 0.001$) with an R^2 of 0.84. This was expected, as specific power is a linear function of application rate (eq. 2). The significance of the relationship is that efforts by center-pivot sprinkler manufacturers to develop sprinklers with greater wetted radius to reduce composite average water application rates has also tend to reduced composite average specific power. However, sprinkler composite average application rate cannot be used interchangeably with average composite specific power, as the correlation coefficient is not equal to 1. The increasing variability in average composite specific power with increasing composite average water application rate demonstrates that some relatively large drops from center-pivot sprinklers needed to increase the wetted radius and reduce the composite application rate do not necessarily result in a substantially greater transfer of kinetic energy to the soil. For example, contrast the I-Wob black plate and blue plate sprinklers at 103 kPa with 7.94 mm nozzles having equal flow rates. The I-Wob black plate sprinkler has an average composite specific power of 0.159 W m^{-2} (table 2), while

Table 5. Sprinklers that have the maximum and minimum average composite specific power (*SP*) in units of W m^{-2} as influenced by flow rate and operating pressure.

Pressure (kPa)	Flow Rate Range: Low	Medium	High
Minimum *SP*			
69	I-Wob Gray (0.024)	I-Wob Gray (0.066)	I-Wob Gray (0.129)
103	I-Wob Gray (0.023)	I-Wob Gray (0.056)	I-Wob Gray (0.122)
138	I-Wob Gray (0.024)	I-Wob Gray (0.057)	I-Wob Gray (0.127)
Maximum *SP*			
69	I-Wob White (0.037)	I-Wob White (0.101)	I-Wob Blue (0.244)
103	I-Wob Blue (0.031)	I-Wob White (0.095)	O3000 Black (0.230)
138	O3000 Black (0.039)	I-Wob Blue (0.108)	I-Wob White (0.229)

the I-Wob blue plate sprinkler has an average composite specific power of 0.228 W m^{-2}, or 43% greater specific power with very similar average composite water application rates. These sprinklers have very similar ranges in drop sizes (data not shown) but substantially different radial water application rates. The I-Wob black plate sprinkler has a relatively small water application rate near the outer radial extent, while the I-Wob blue plate sprinkler has a much higher application near the outer radial extent (data not shown), resulting in a greater peak in specific power at the outer radial extent, resulting in greater average composite specific power. The manner in which water is applied (radial application rate profile) is nearly as important as drop size for determination of average composite specific power and applied kinetic energy. Average composite specific power is based on the sum of drop size classes and not just a single drop size. Thus, if there are few large droplets, then the overall kinetic energy applied will not be greatly affected.

Maximum and minimum average composite specific power as influenced by sprinkler, flow rate, and pressure are summarized in table 5. The I-Wob gray plate sprinkler provided the lowest average composite specific power for the sprinklers tested. For the high flow rate, average composite specific power varied by up to 89% among the sprinklers tested. The effect that specific power has on bare soil infiltration rate was demonstrated by Thompson and James (1985) and Mohammed and Kohl (1987) using rainfall simulators and is depicted in figure 4. For the high flow rate sprinklers at 103 kPa, the average composite specific power ranged from 0.122 for the I-Wob gray plate sprinkler to 0.230 W m^{-2} for the O3000 sprinkler. Assuming that average composite specific power is analogous to specific power of a rainfall simulator, the depth of water infiltrated prior to ponding would be approximately 35 mm and 58 mm for the I-Wob gray plate sprinkler and 28 mm and 32 mm for the O3000 sprinkler for the Warden silt loam and Vienna loam soils, respectively. Sprinkler selection can have a substantial effect on infiltration rate of bare soil, which results in a substantial effect on depth infiltrated, runoff, and erosion. The effect of specific power on depth of water infiltrated prior to ponding, shown in figure 4, is for freshly tilled bare soil. Once a soil surface seal is formed by previous irrigation or rainfall, specific power has

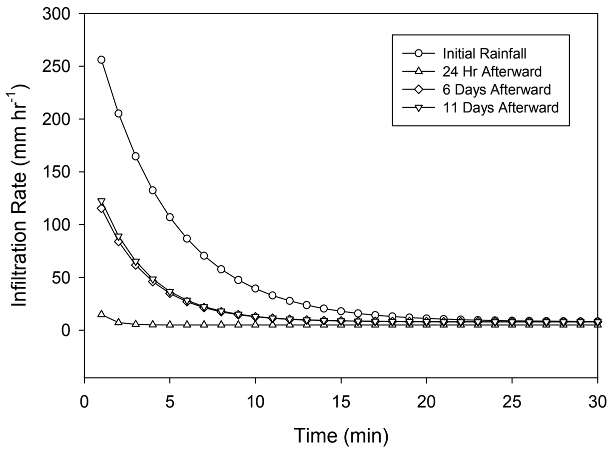

Figure 5. Effect of soil surface seal formation on infiltration of subsequent rainfall at 24 h, 6 d, and 11 d intervals after an initial rainfall event (after Morin and Benyamini, 1977).

much less influence on infiltration rate, and peak or average application rate will be a controlling factor in runoff and erosion. Morin and Benyamini (1977) demonstrated the effect that development of a soil surface seal has on infiltration of subsequent rainfall events (fig. 5). The average 1 to 30 min infiltration rate was 48.2, 5.4, 20.2, and 21.0 mm h^{-1} for the initial rainfall event and subsequent rainfall at 24 h, 6 d, and 11 d intervals following the initial rainfall event, respectively. Duration of rainfall events, rather than specific power, after soil surface seal formation will largely determine the depth of water infiltrated. Thus, the I-Wob gray sprinkler may result in greater infiltrated depth on bare freshly tilled soil than the O3000 sprinkler. However, once a surface seal is formed, the O3000 sprinkler may result in greater infiltrated depth and less erosion due to its 11% lower average composite application rate (table 2) resulting from a larger wetted diameter. King and Bjorneberg (2011) found that sprinkler wetted diameter had a greater impact on runoff and erosion than sprinkler type. If vegetation or surface residue is present to prevent or limit soil surface seal formation (depending on the soil saturated hydraulic conductivity), the sprinkler with the lowest average application rate may also result in greater infiltrated depth and less runoff. Thus, the sprinkler with larger drops (resulting in higher droplet kinetic energy, greater wetted diameter, and lower average composite water application rate) may be the best sprinkler with regard to depth of water infiltrated, runoff, and erosion. The actual result will depend upon soil physical characteristics, soil surface conditions, and sprinkler characteristics. Due to the influence of soil physical characteristics and soil surface conditions, droplet kinetic energy or average composite specific power is not suitable as a single parameter to select between sprinkler choices.

CONCLUSION

Kinetic energy applied by common commercial moving spray-plate sprinklers that use "off-center" action to rotate the spray-plate was characterized over a range of flow rates and operation pressures using two methods. Specific power represents the rate at which kinetic energy per unit area is transferred to the soil as a function of distance from a sprinkler and is analogous to a sprinkler radial water application rate distribution. Specific power was used to estimate actual kinetic energy transferred to the soil by overlapping specific power profiles of sprinklers equally spaced 3 m along a center-pivot lateral. The kinetic energy of irrigation sprinklers has traditionally been characterized using area-weighted kinetic energy per unit sprinkler discharge. This method heavily weights the effects of the largest drops, which travel farthest from the sprinkler and have the largest kinetic energy, and does not account for the volume of water applied by each drop size. Kinetic energy per unit volume of sprinkler discharge is correlated to actual kinetic energy transferred to the soil by the sprinklers, but it does not represent droplet kinetic energy applied to the soil, as the correlation coefficient is not equal to 1. Droplet kinetic energy for a given flow rate and operating pressure varied by up to 200% among the sprinklers evaluated. Designing sprinklers that minimize kinetic energy transferred to bare soil will require a monotonic decreasing application rate with radial distance, as any peak in application rate at large radial distances will result in a peak in specific power. Kinetic energy per unit drop volume will always increase with radial distance, as drops sizes get larger with radial distance. The sprinkler with the lowest droplet kinetic energy applied or the lowest average composite specific power may not necessarily be the sprinkler that results in the greatest infiltrated depth or the least runoff and erosion. Thus, droplet kinetic energy is not suitable as a single parameter to select between sprinkler choices.

ACKNOWLEDGEMENTS

This research is partially supported by a Cooperative Research and Development Agreement (No. 58-3K95-9-1311) with Nelson Irrigation Corp., Walla Walla, Washington. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of Nelson Irrigation Corp.

REFERENCES

Agassi, M., J. Morin, and I. Shainberg. 1985. Effect of impact energy and water salinity on infiltration rate on sodic soils. *SSSA J.* 49(1): 186-189.

Agassi, M., D. Bloem, and M. Ben-Hur. 1994. Effect of drop energy and soil and water chemistry on infiltration and erosion. *Water Resources Res.* 30(4): 1187-1193.

Assouline, S., and Y. Maulem. 1997. Modeling the dynamics of seal formation and its effect on infiltration as related to soil and rainfall characteristics. *Water Resources Res.* 33(7): 1527-1536.

Ben-Hur, M., I. Shainberg, and J. Morin. 1987. Variability of infiltration in a field with surface-sealed soil. *SSSA J.* 51(10): 1299-1302.

Ben-Hur, M., Z. Plaut, G. J. Levy, M. Agassi, and I. Shainberg. 1995. Surface runoff, uniformity of water distribution, and yield of peanut irrigation with a moving sprinkler system. *Agron. J.* 87(4): 609-613.

Betzalel, I., J. Morin, Y. Benyamini, M. Agassi, and I. Shainberg. 1995. Water drop energy and soil seal properties. *Soil Sci.* 159(1): 13-22.

Borst, H. L., and R. Woodburn. 1942. The effect of mulching and methods of cultivation on runoff and erosion from Muskingum silt loam. *Agric. Eng.* 23(1): 19-22.

DeBoer, D. W. 2002. Drop and energy characteristics of a rotating spray-plate sprinkler. *J. Irrig. and Drain. Eng.* 128(3): 137-146.

DeBoer, D. W., D. L. Beck, and A. R. Bender. 1992. A field evaluation of low, medium, and high pressure sprinklers. *Trans. ASAE* 35(4): 1185-1189.

DeBoer, W. B., and S. T. Chu. 2001. Sprinkler technologies, soil infiltration, and runoff. *J. Irrig. and Drain. Eng.* 127(4): 234-239.

Duley, F. L. 1939. Surface factors affecting the rate of intake of water by soils. *SSSA Proc.* 4: 60-61.

Ellison, W. D. 1945. Some effects of raindrops and surface flow on soil erosion and infiltration. *Trans. American Geophys. Union* 26(3): 415-429.

Hasheminia, S. M. 1994. Controlling runoff under low-pressure center-pivot irrigation systems. *Irrig. and Drain. Systems* 8(1): 25-34.

Kincaid, D. C. 1996. Spraydrop kinetic energy from irrigation sprinklers. *Trans. ASAE* 39(3): 847-853.

King, B. A., and D. L. Bjorneberg. 2009. Potential runoff and erosion comparison of four center-pivot sprinklers. ASABE Paper No. 095942. St. Joseph, Mich.: ASABE.

King, B. A., and D. L. Bjorneberg. 2010. Characterizing droplet kinetic energy applied by moving spray-plate center-pivot irrigation sprinklers. *Trans. ASAE* 53(1): 137-145.

King, B. A., and D. L. Bjorneberg. 2011. Evaluation of potential runoff and erosion of four center-pivot irrigation sprinklers. *Applied Eng. in Agric.* 27(1): 75-85.

King, B. A., T. W. Winward, and D. L. Bjorneberg. 2010. Laser precipitation monitor for measurement of drop size and velocity of moving spray-plate sprinklers. *Applied Eng. in Agric.* 26(2): 263-271.

McIntyre, D. S. 1958. Permeability measurements of soil crusts formed by raindrop impact. *Soil Sci.* 85(4): 185-189.

Mohammed, D., and R. A. Kohl. 1987. Infiltration response to kinetic energy. *Trans. ASAE* 30(1): 108-111.

Morin, J., and Y. Benyamini. 1977. Rainfall infiltration into bare soils. *Water Resources Res.* 13(5): 813-817.

Silva, L. L. 2006. The effect of spray head sprinklers with different deflector plates on irrigation uniformity, runoff, and sediment yield in a Mediterranean soil. *Agric. Water Mgmt.* 85(5): 243-252.

Thompson, A. L., and L. G. James. 1985. Water droplet impact and its effect on infiltration. *Trans. ASAE* 28(5): 1506-1510.

Undersander, D. J., T. H. Marek, and R. N. Clark. 1985. Effect of nozzle type on runoff and yield of corn and sorghum under center-pivot sprinkler systems. *Irrig. Sci.* 6(1): 107-116.

Von Bernuth, R. D., and J. R. Gilley. 1985. Evaluation of center-pivot application packages considering droplet-induced infiltration reduction. *Trans. ASAE* 28(6): 1940-1946.