Determination of Kinetic Energy Applied by Center Pivot Sprinklers

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Abstract. *The kinetic energy of discrete drops impacting a bare soil surface is generally observed to lead to a drastic reduction in water infiltration rate due to soil surface seal formation. 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. In the design of center pivot irrigation systems, selection of sprinklers with minimum applied kinetic energy could potentially minimize seasonal runoff and erosion hazard. Size and velocity of drops from five common center pivot sprinklers were measured using a laser in the laboratory. The data were used to calculate kinetic energy transferred to the soil by each sprinkler on a center pivot irrigation system lateral with 2.5 m spacing between sprinklers. Specific power, which represents the rate that kinetic energy is transferred to the soil as a function of distance from a sprinkler and analogous to a sprinkler radial water application rate distribution, was used to estimate actual kinetic energy transferred to the soil by overlapping specific power profiles of sprinklers equally spaced along a center pivot lateral. Kinetic energy of irrigation sprinklers has traditionally been characterized using area weighted kinetic energy per unit drop volume. This characterization was found not to be correlated to actual kinetic energy transferred to the soil by the sprinklers. The results demonstrated that sprinklers with the smallest drop sizes do not necessarily transfer the least kinetic energy per unit depth of water applied. Conversely, sprinklers with the largest drop sizes do not necessarily transfer the greatest kinetic energy to the soil.*

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

Introduction

When discrete water drops impact a bare soil surface a drastic reduction in water infiltration rate is generally observed due to compaction, aggregate destruction, soil particle detachment, dispersion, and in-depth wash-in of fine particles. These physical processes reduce surface soil porosity and pore size distribution to create a soil surface seal with reduced hydraulic conductivity that expands in size and depth with time (Assouline and Mualem, 1997). The effect soil surface seal formation has on water infiltration rate has been studied by Agassi et al. (1984,1985), Thompson and James (1985), Mohammed and Kohl (1987), Ben-Hur et al. (1987) and Assouline and Maulem, (1997). These studies have shown that 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 sealing. 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 leading to a reduction in water infiltration rate in combination with high water application rates under center pivot sprinkler irrigation exacerbates potential runoff and erosion hazard.

The effect kinetic energy applied by center pivot sprinklers has on infiltration and runoff is well known in the center pivot sprinkler irrigation industry. Over the past two decades, center pivot sprinkler manufacturers have continued to develop sprinklers that reduce peak water application rates and droplet kinetic energy as a means to sustain water infiltration rates and reduce potential runoff and erosion hazard. Consequently, there are numerous center pivot sprinkler choices available to the center pivot sprinkler irrigation system designer and producer but limited quantitative information that relates these choices to performance in regards to infiltration, runoff and erosion. Kincaid (1996) developed a model to estimate kinetic energy per unit drop volume from common sprinkler types as a function of nozzle size and operating pressure to be used as a design aid in selecting center pivot sprinklers. DeBoer (2002) evaluated the kinetic energy per unit drop volume from 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. Values of kinetic energy per unit drop volume are largely dependent upon the drop size characteristics of the sprinklers. Sprinklers with relatively large drop sizes have the highest kinetic energy values and sprinklers with relatively small drop sizes have the lowest kinetic energy values. The drop size distribution of a sprinkler has a substantial influence on the wetted diameter and application rate distribution profile. In general, sprinklers with relatively small drop sizes have relatively small wetted diameters and result in higher application rates when application rate pattern profiles are overlapped along a center pivot lateral. Sprinklers with relatively large drop sizes have relatively large wetted diameters and result in lower application rates when application pattern profiles are overlapped along a center pivot lateral. In regards to runoff and erosion, any benefits associated with lower applied kinetic energy from smaller drops are reduced or eliminated due to the higher application rate which often exceeds the water infiltration rate of the soil. Consequently, values of kinetic energy per unit drop volume do not identify an optimum sprinkler selection, and thus have not proved very useful in center pivot sprinkler irrigation system design.

King and Bjorneberg (2009) evaluated runoff and erosion from five common center pivot sprinklers on multiple soils and found significant differences between center pivot sprinkler types of equal flow rates. Estimated values of kinetic energy per unit drop volume from the models of Kincaid (1996) and DeBoer (2002) did not correlate with measured runoff or erosion rates. The objectives of this study was to evaluate the kinetic energy applied to the soil in the center pivot sprinkler experiments of King and Bjorneberg (2009) and compare the results with kinetic energy per unit volume used to characterize sprinkler kinetic energy.

Methods and Materials

Sprinklers used in this study and corresponding operating pressures and nozzle sizes are listed in table 1. Sprinkler types and operating pressures were selected to be representative of field installations on center pivot sprinkler irrigation systems in southern Idaho. Sprinkler nozzle sizes were selected to provide nearly equal flow rates among sprinklers at high and low flow rates at the given operating pressures, based on manufacturer data. The high flow rate nozzle is representative of that found near the end of the lateral on 390 m long center pivot sprinkler irrigation systems in southern Idaho.

Table 1. Sprinklers and corresponding operating pressure, nozzle diameter and flow rate used in study.

Sprinkler	Pressure kPa	Nozzle Diameter mm	Flow Rate* L/min
High Flow Rate			
Senninger I-Wob Standard 9-groove Plate	103	8.33	43.2
Nelson R3000 Brown Plate	138	7.54	42.7
Nelson R3000 Red Plate	138	7.54	42.7
Nelson S3000 Purple Plate	103	8.14	43.5
Nelson D3000 Flat Plate	103	8.14	43.5
Low Flow Rate			
Senninger I-Wob Standard 9-groove Plate	103	5.55	19.8
Nelson R3000 Brown Plate	138	5.36	21.2
Nelson R3000 Red Plate	138	5.36	21.2
Nelson S3000 Purple Plate	103	5.75	21.4

*Manufacturer's published data.

Drop sizes and drop velocities from the sprinklers were measured using a Thies Clima Laser Precipitation Monitor (TCLPM) (Adolf Thies GmbH & Co. KG, Göttingen Germany) (King et al., 2009). The tests were conducted in the laboratory and represent a no wind condition. Drop size and velocity measurements were collected at 1 m increments from the sprinkler. A minimum of 10,000 drops were measured at each measurement 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 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 during a test. Pressure values were within ±7 kPa of the nominal pressure rating. Specific details of the experimental methods are provided by King et al. (2009).

Radial application rate distributions for the sprinklers were also determined in the laboratory. Catch cans, 15 cm in diameter and 18 cm tall spaced at 0.5 m increments from the sprinkler in one radial direction, were used to collect water. Sprinkler height was 0.8 m above can opening. The duration of each test was 30 to 60 minutes. 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.

Area weighted kinetic energy per unit drop volume, KE_d (J/L), of each sprinkler was computed as:

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

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) of the jth drop and A_i is the wetted area (m^2) associated with ith radial location. The resulting value represents the average kinetic energy per liter of drop volume applied over the wetted area (Kincaid, 1996; DeBoer 2002).

The specific power, SP (W/m^2), as a function of radial measurement location for each sprinkler was computed as:

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

SP represents the time derivative of kinetic energy per unit area i.e. 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 (e.g. Thompson and James, 1985). A sprinkler radial SP distribution is analogous to a sprinkler radial water application rate distribution. Just as the depth of water applied by a center pivot sprinkler irrigation system can be determined by integrating with respect to time the composite overlapped sprinkler application rate distribution perpendicular to the sprinkler lateral, the kinetic energy applied by a center pivot irrigation system can be determined by integrating with respect to time the composite overlapped sprinkler SP distribution perpendicular to the sprinkler lateral.

A sprinkler overlap model written in Visual Basic was used to compute the composite water application rate distribution perpendicular to the sprinkler lateral. The sprinkler overlap model used a 0.3 m distance increment in determining the composite water application rate distribution. The sprinkler application rate distributions determined in the laboratory were used in the sprinkler overlap model. The sprinkler application rate distributions were interpolated to 0.3 m distance increments using cubic spline interpolation between catch can measurements. Modeled sprinkler spacing along the lateral was 2.5 m.

Water application depth was determined by numerically integrating the composite sprinkler application rate distribution perpendicular to the sprinkler lateral with time. The time required by the sprinkler lateral to pass over a location and apply 25 mm of water was numerically determined by adjusting the integration time period (sprinkler lateral travel speed).

The sprinkler overlap model was also used to compute the composite SP distribution perpendicular to the sprinkler lateral with time. The SP distribution was determined at 0.3 m increments based on cubic spline interpolation of the SP_i at each *i*th radial measurement location (equation 2). The kinetic energy applied by 25 mm of water application was determined by numerically integrating the composite SP distribution perpendicular to the sprinkler lateral using the same time period required to apply 25 mm of water. Applied kinetic energy per unit volume of water application, KE_a (J/ m^2 mm), was determined by dividing the total applied kinetic energy by the depth of water application (25 mm). Total kinetic energy applied by irrigation can then be determined by multiplying KE_a by the applied irrigation depth.

Results and Discussion

Measured drop size distributions for the five high flow rate sprinklers used in the study are shown in figure 1. The drop size distribution of the D3000 sprinkler had the smallest range in drop size and the smallest maximum drop size (approximately 3.0 mm) of the five sprinklers. Approximately 90% of the applied water volume (d_{90}) was from drops less than 2.0 mm in diameter. The I-Wob sprinkler had the largest range in drop size with a maximum drop size of approximately 5.5 mm in diameter. Although the R3000 red plate and S3000 sprinklers both use 6-groove moving spray-plates, the d_{30} through d_{80} drop sizes of the R3000 red plate sprinkler were slightly smaller than the S3000 sprinkler. This is largely due to the higher pressure used with the R3000 red plate sprinkler. This outcome was unexpected as the S3000 sprinkler is generally considered to provide smaller drops that are less destructive to the soil surface structure with lower operating pressure. The R3000 brown plate sprinkler had a range in drop size similar to the R3000 red plate and S3000 sprinklers. Surprisingly though the d_{10} through d_{98} drop sizes of the R3000 brown plate sprinkler were smaller than for the R3000 red plate, S3000 and I-Wob sprinklers. Based solely on measured drop size distributions and the fact that larger drops possess greater kinetic energy, the relative ranking of the sprinklers would rank the I-Wob as having the greatest potential destructive effect on soil structure and the D3000 having the least potential destructive effect.

Measured drop size distributions for the four low flow rate sprinklers used in the study are shown in figure 2. The relative ranking of the sprinklers based on drop size changed with nozzle flow rate. The R3000 red plate and I-Wob sprinklers have very similar drop size distributions at the low flow rate with nearly the same maximum drop size of approximately 4.5 mm. The S3000 sprinkler has the smallest fraction of water applied over the 1.3 to 3.5 mm drop size and a relatively large fraction of water is applied over the drop size range of 3.5 to 4.1 mm as evident from the steep increase in cumulative volume over this range in drop size. The R3000 brown plate sprinkler has the largest range in drop size with a maximum drop size of approximately 5.2 mm. Based solely on measured drop size distributions the R3000 brown plate sprinkler would have the greatest potential destructive effect on soil structure.

Radial application rate distributions for each of the five high flow rate sprinklers used in the study are shown on figure 3. The I-Wob and R3000 brown plate sprinkler had the largest wetted radiuses of the five sprinklers and the D3000 had the smallest wetted radius. The wetted radius of each sprinkler was correlated with the largest drop size of each sprinkler. The I-Wob and R3000 brown plate sprinklers had the largest drop sizes and hence the largest wetted radiuses of the five sprinklers. These sprinklers had about a one meter greater wetted radius than the S3000 and R3000 red plate sprinklers.

Radial application rate distributions for each of the four low flow rate sprinklers used in the study are shown in figure 4. The I-Wob, S3000 and R3000 red plate sprinklers all have nearly the same wetted radius at the low flow rate. The R3000 brown plate sprinkler has the largest wetted radius, approximately 0.6 m larger, which is consistent with having in the largest drop size distribution and drop size (fig. 2).

Computed KE_d values for each of the five high flow rate sprinklers are shown in table 2. Based on KE_d, the I-Wob had the highest kinetic energy and the D3000 had the lowest. This was expected based on the drop size distributions for the two sprinklers (fig. 1) and the fact that calculation of kinetic energy based on equation 1 is area weighted, which heavily weights the largest drops that travel the farthest from the sprinkler and have the greatest kinetic energy. The relative ranking of the R3000 red and brown plate and S3000 sprinklers based on KE_d were essentially reversed from the ranking based on d_{90} drop sizes. The R3000 brown plate sprinkler, which had the smallest d_{10} through d_{95} drop sizes of the three sprinklers, had the largest KE_d value of the three sprinklers. This was due to the area weighting associated with equation 1. The R3000 brown plate sprinkler had the largest d_{98} to d_{100} drop sizes of the three sprinklers which travel farther from the sprinkler (fig. 3) and are heavily weighted even though the largest drops constitute less than 2% of total sprinkler volume. This outcome suggests that area weighted kinetic energy per unit drop volume is not necessarily a good indicator of kinetic energy transferred to the soil by irrigation sprinklers, but has traditionally been

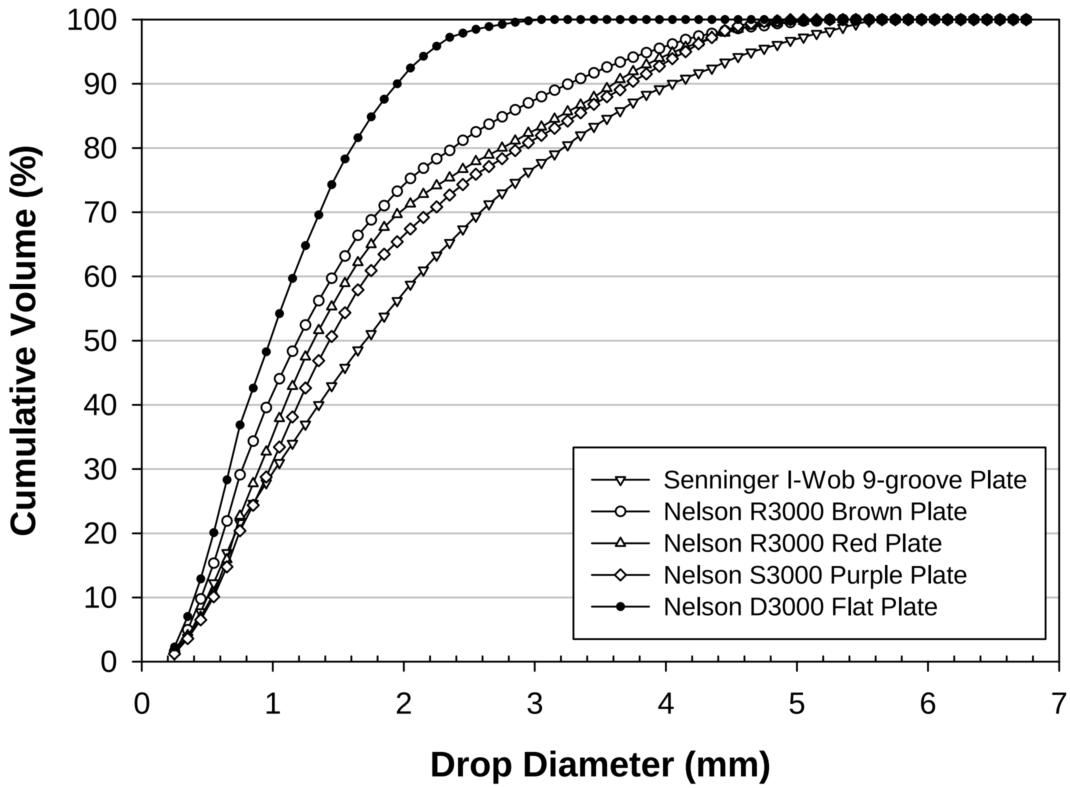

Figure 1. Drop size distribution of high flow rate sprinklers used in study.

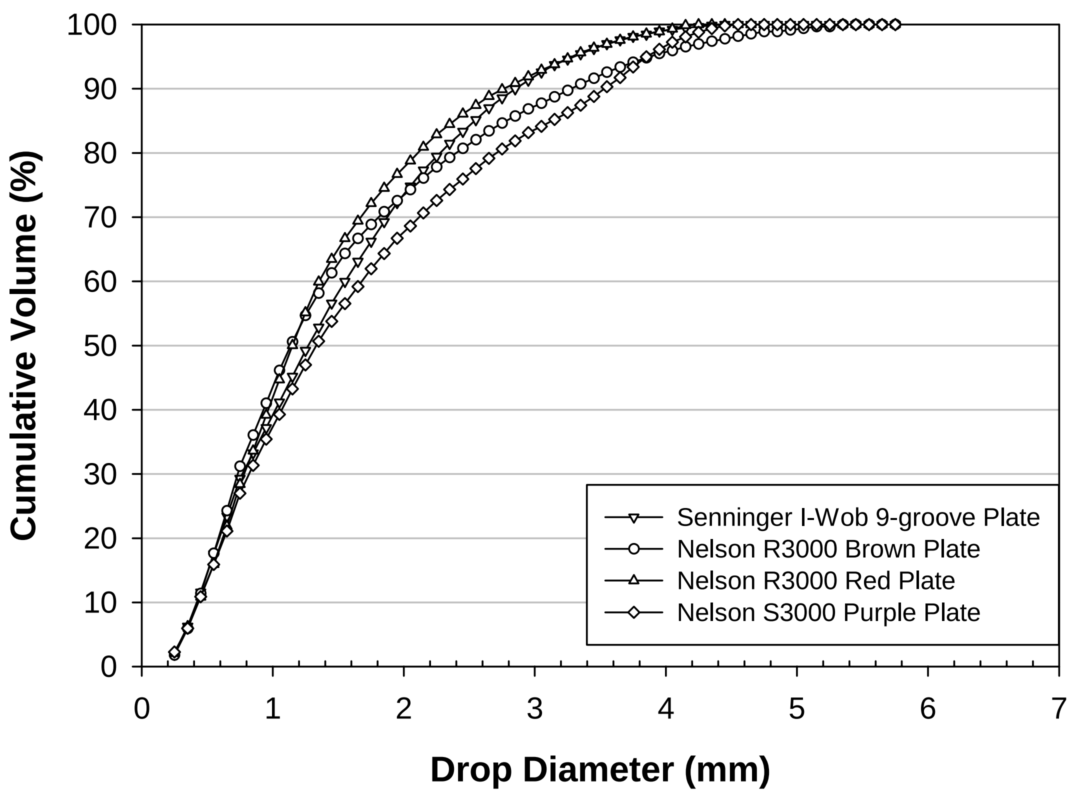

Figure 2. Drop size distribution of low flow rate sprinklers used in study.

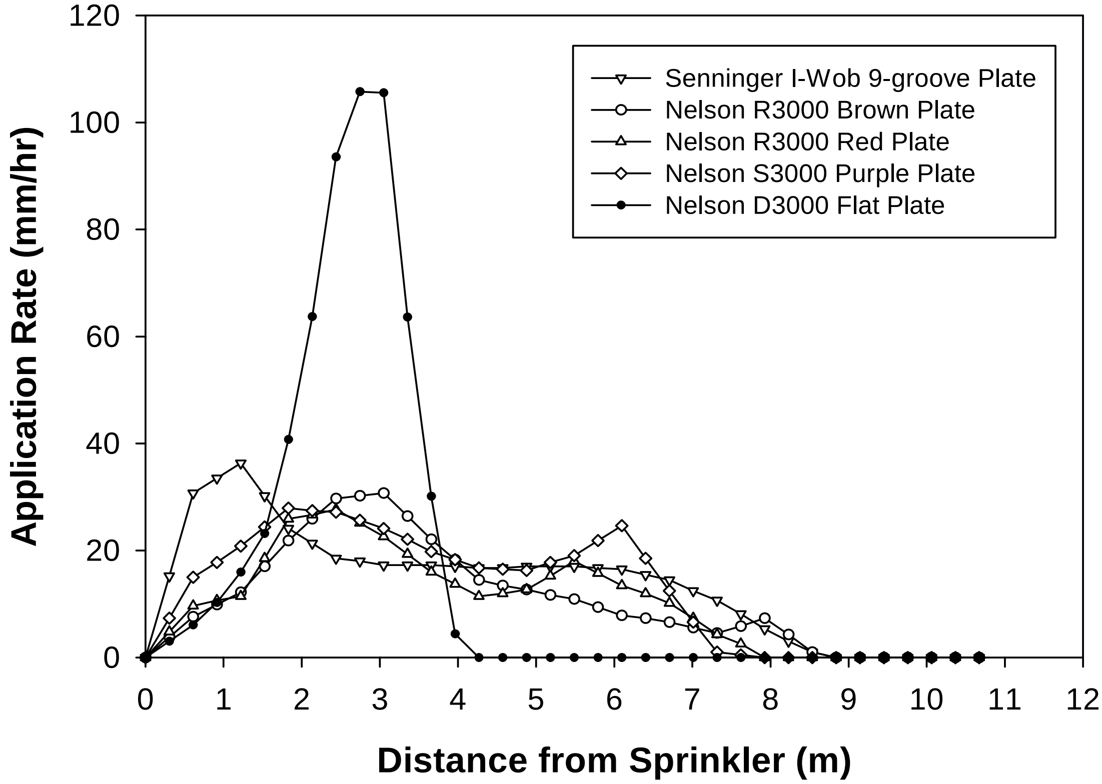

Figure 3. Radial application rate of high flow rate sprinklers used in study.

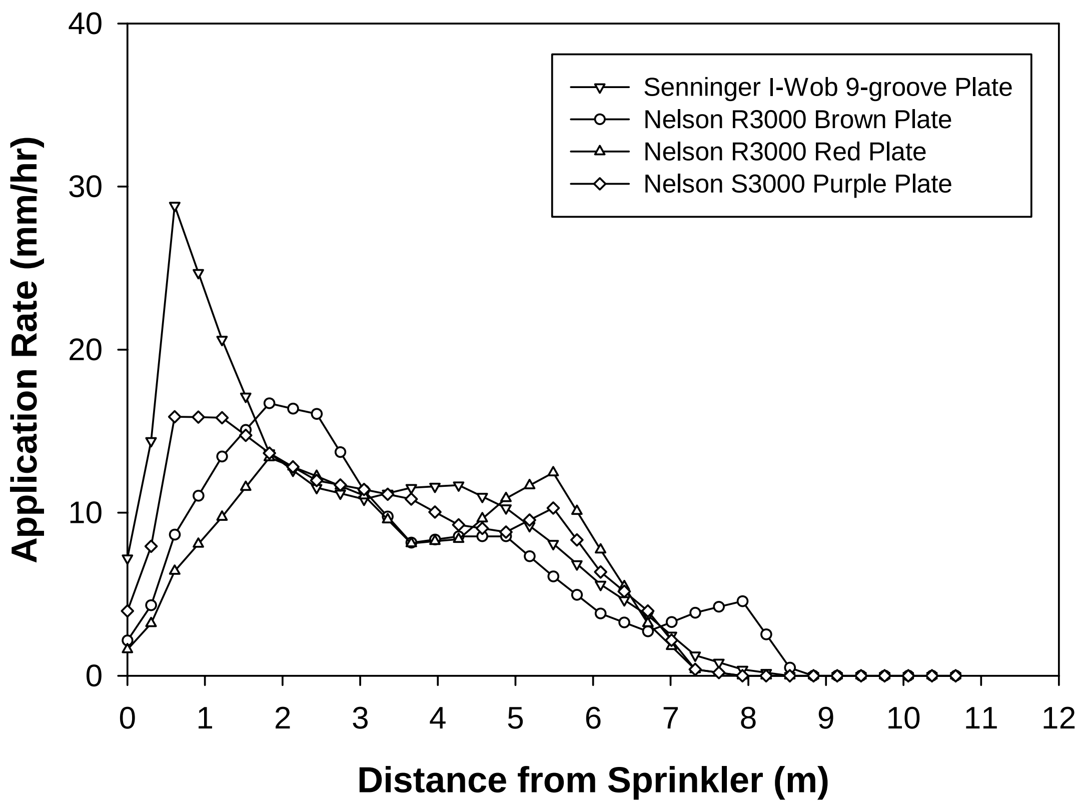

Figure 4. Radial application rate of low flow rate sprinklers used in this study.

Table 2. Computed kinetic energy per unit drop volume (KE_d) and applied kinetic energy per unit irrigation depth (KE_a) for each sprinkler used in study.

Sprinkler	KE_d J/L	KE_a J/m^2 mm
High Flow Rate		
Senninger I-Wob Standard 9-groove Plate	13.7	11.0
Nelson R3000 Brown Plate	13.5	9.7
Nelson R3000 Red Plate	13.3	12.2
Nelson S3000 Purple Plate	12.2	10.9
Nelson D3000 Flat Plate	8.6	11.8
Low Flow Rate		
Senninger I-Wob Standard 9-groove Plate	9.7	8.1
Nelson R3000 Brown Plate	12.1	9.4
Nelson R3000 Red Plate	10.1	9.0
Nelson S3000 Purple Plate	11.2	9.8

used to compare relative potential soil surface destructive effect of sprinklers (Kincaid, 1996; DeBoer, 2002).

Computed KE_d values for each of the four low flow rate sprinklers are also shown in table 2. Based on KE_d, the I-Wob sprinkler had the lowest kinetic energy and the R3000 brown plate sprinkler had the highest. The R3000 brown plate sprinkler had the highest KE_d because it had the largest drop size and largest wetted radius which is heavily weighted by equation 1. The S3000 sprinkler had the second highest KE_d because it had the second largest fraction of d_{98} to d_{100} drop sizes which travel the farthest from the sprinkler and are heavily weighted by equation 1.

Computed SP values for each of the five high flow rate sprinklers as a function of radial distance from the sprinkler are shown in figure 5. The D3000 sprinkler had the greatest peak SP value of all the sprinklers; approximately five times that of the other sprinklers. This outcome was not expected given the D3000 sprinkler had the smallest drop sizes of all the five sprinklers. This outcome demonstrates that despite the relatively small drop sizes of the D3000 sprinkler, kinetic energy is transferred to the soil surface at a relatively high rate due to the relatively small wetted radius of the sprinkler. The S3000 sprinkler has the second highest peak specific power due to the relative large drop size (fig. 1) and high peak application rate at a radial distance of 6.3 m (fig. 3). If peak specific power is a primary factor in soil surface seal formation and sheet erosion, the D3000 and S3000 sprinklers would not be sprinklers of choice. This outcome is contrary to conventional practice of recommending spray and spinner type sprinklers for soils susceptible to surface sealing. Thompson and James (1985) and Mohammed and Kohl (1987) found that as specific power increased, water infiltrated prior to ponding decreased, indicating that peak specific power maybe a primary factor in soil surface seal formation.

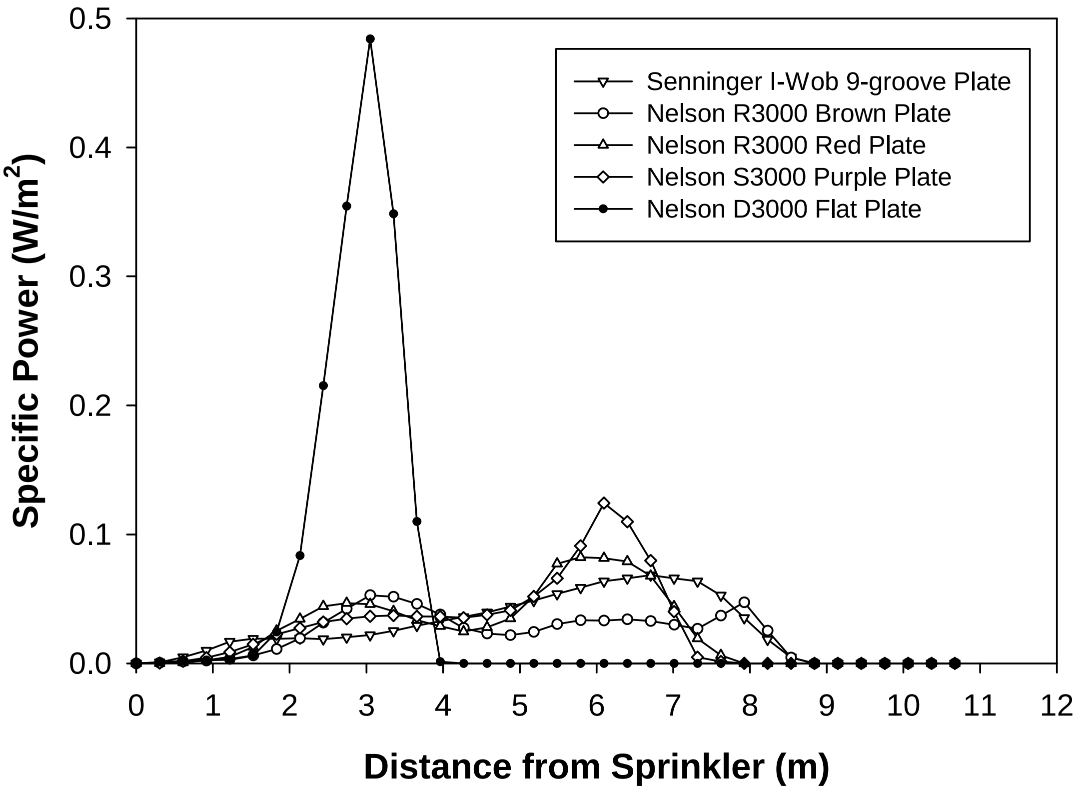

Figure 5. Radial specific power application pattern for high flow rate sprinklers used in study.

Computed SP values for each of the four low flow rate sprinklers as a function of radial distance from the sprinkler are shown in figure 6. The S3000 and R3000 red plate sprinklers have the highest and nearly identical peak specific power. This nearly equal peak specific power 5.6 m from the sprinkler is a result of the S3000 sprinkler having larger drops (fig. 2) and a lower application rate at 5.6 m from the sprinkler (fig. 4) and the R3000 red plate sprinkler having smaller drops and higher application rate at 5.6 m from the sprinkler which balance out in equation 2. The I-Wob sprinkler has the lowest peak specific power but only slightly lower than the R3000 brown plate sprinkler. The peak specific power for these two sprinklers coincides with the peak in application rates (fig. 4) demonstrating the effect application rate plays in determining specific power.

Composite water application rate distributions computed by the sprinkler overlap model are shown in figure 7 for each of the five high flow rate sprinklers used in the study. The composite water application rate distribution shown in figure 7 is an average rate between adjacent sprinklers spaced 2.5 m along the lateral. The horizontal axis in figure 7 is time rather than distance and represents time for the center pivot sprinkler lateral to pass over a fixed location. The area under each composite application rate distribution shown in figure 7 represents 25 mm of water application. Time average composite water application rates for the five sprinklers are given in table 3. The R3000

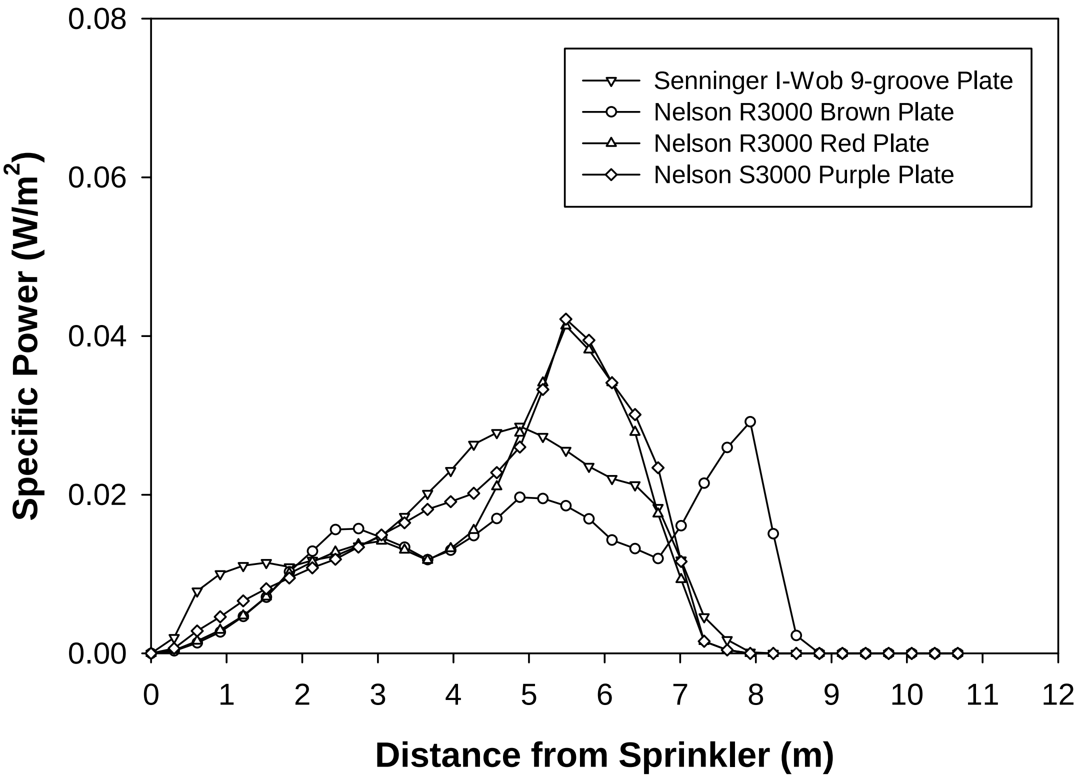

Figure 6. Radial specific power application pattern for low flow rate sprinklers used in study.

brown plate sprinkler had the lowest average composite water application rate and the D3000 sprinkler had the greatest. The average composite water application rate of each sprinkler is inversely related to sprinkler wetted radius since the flow rates of the sprinklers (based on manufacturer's published data) were nearly equal and sprinkler spacing along the lateral was equal.

Time average composite water application rates for the four low flow rate sprinklers are also given in table 3. The application rates are very similar since the flow rates of the sprinklers were nearly equal and sprinkler spacing along the lateral was equal. The R3000 brown plate sprinkler had the lowest application rate since it had the largest wetted radius of the four sprinklers.

Composite specific power distributions computed by the sprinkler overlap model using 2.5 m sprinkler spacing are shown in figure 8 for each of the five high flow rate sprinklers used in the study. The composite specific power shown in figure 8 is average specific power between adjacent sprinklers along the lateral. The horizontal axis in figure 8 is time and equivalent to that of figure 7 for each sprinkler. The area under each composite specific power distribution represents the total kinetic energy applied per unit area (J/m^2) for an irrigation application depth of 25 mm. The total kinetic energy applied by each sprinkler with 25 mm of water application is included in the legend of

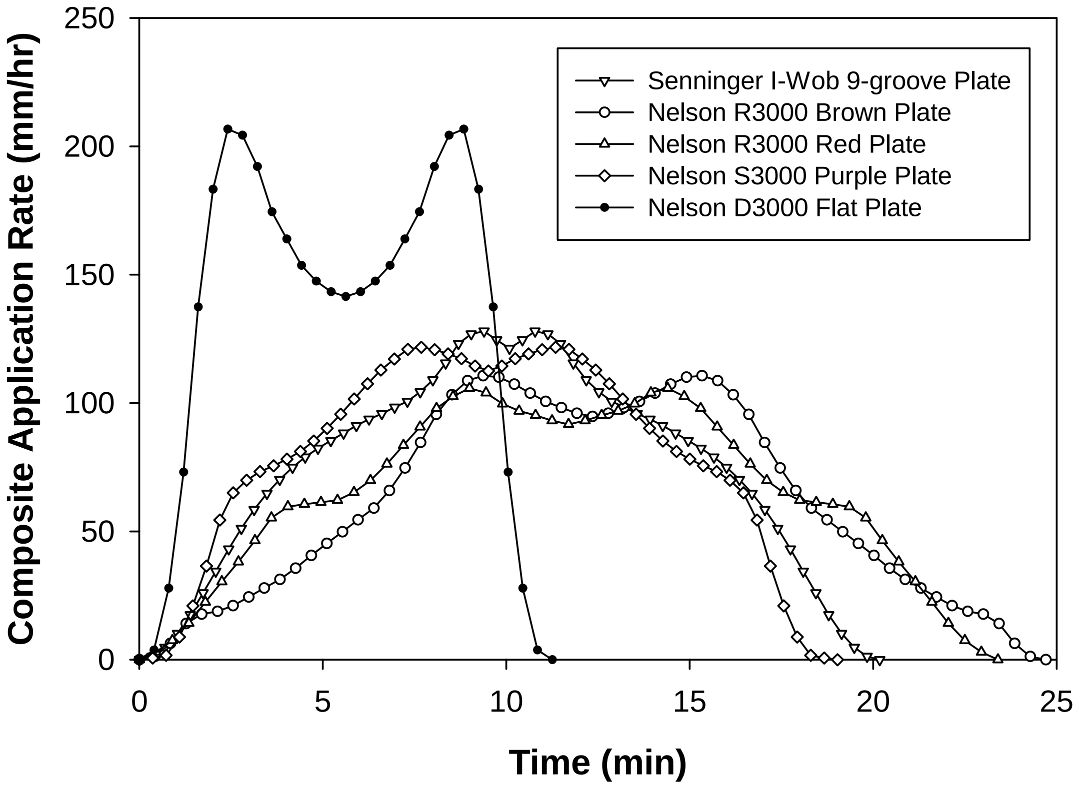

Figure 7. Composite application rate profile perpendicular to sprinkler lateral for each of the five high flow rate sprinklers used in the study. Sprinkler spacing along the lateral was 2.5 m. Time duration of each application rate pattern represents the time required for the irrigation system to apply an irrigation depth of 25 mm.

Table 3. Time averaged composite water application rate and time averaged composite specific power computed by sprinkler overlap program for each sprinkler used in study.

Sprinkler	Application Rate mm/hr	Specific Power W/m^2
High Flow Rate		
Senninger I-Wob Standard 9-groove Plate	73.3	0.224
Nelson R3000 Brown Plate	59.5	0.161
Nelson R3000 Red Plate	63.6	0.215
Nelson S3000 Purple Plate	77.2	0.234
Nelson D3000 Flat Plate	129.7	0.425
Low Flow Rate		
Senninger I-Wob Standard 9-groove Plate	36.2	0.085
Nelson R3000 Brown Plate	34.0	0.086
Nelson R3000 Red Plate	36.6	0.092
Nelson S3000 Purple Plate	36.8	0.100

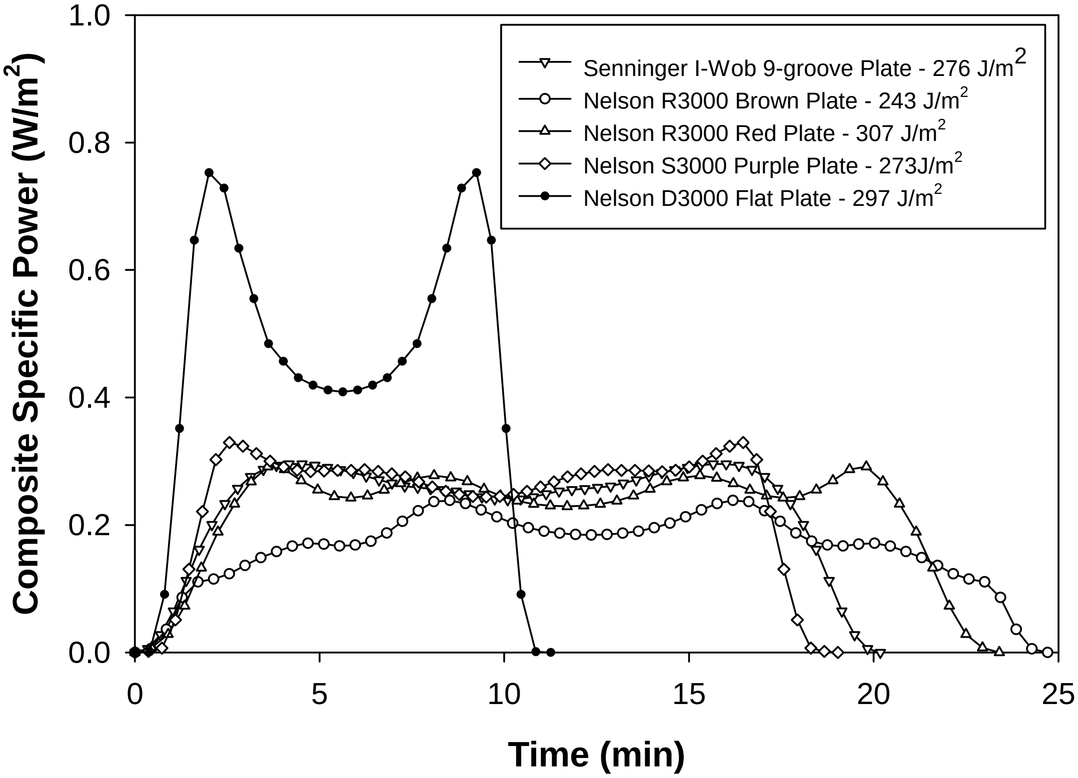

Figure 8. Composite specific power application profile perpendicular to sprinkler lateral for each of the five high flow rate sprinklers used in the study. Sprinkler spacing along the lateral was 2.5 m. Time duration of each application curve represents the time required for the irrigation system to apply an irrigation depth of 25 mm. The total kinetic energy transferred to a bare soil with an application depth of 25 mm is given in the legend for each sprinkler.

figure 8 for reference. Total kinetic energy per unit depth of water application, KE_a (J/m^2 mm) is shown in table 2 for all sprinklers used in the study. Total kinetic energy per unit depth of water application in units of J/m^2 mm is used because it is a more intuitive unit of measure than J/L but is numerically equivalent to kinetic energy per unit volume applied (J/L) (1 mm of water over 1 m^2 equals 1 L).

The relative ranking of all the sprinklers used in the study based on KE_d and KE_a (table 2) from highest to lowest is given in table 4. Spearman's rank correlation coefficient between KE_d and KE_a is 0.333 and not significant ($p = 0.38$) meaning that KE_d is not an indicator of actual kinetic applied by the center pivot irrigation sprinklers, even though it is currently used to indicate kinetic energy applied by a sprinkler. The relative ranking of the high flow rate sprinklers based on KE_a shows that the R3000 red plate sprinkler had the greatest kinetic energy applied and the R3000 brown plate sprinkler had the lowest kinetic energy applied. It was unexpected these two sprinklers that are hydraulically very similar (only different plate design) would apply the highest and lowest kinetic energy of the five high flow rate sprinklers used in the study. The R3000 red plate sprinkler did not have the largest d_{20} through d_{98} drop sizes but yet had the highest kinetic energy applied of the five high flow rate sprinklers. Another unexpected outcome was that the D3000 sprinkler with the smallest drop sizes would apply the second highest kinetic energy of the five high flow rate sprinklers. This outcome is contrary to conventional thought that center pivot sprinklers with small drop sizes transfer the least kinetic energy to the bare soil surface. This conventional thought follows from characterization of sprinkler kinetic energy based on equation 1 and relatively small drop sizes and wetted radius of the D3000 sprinkler.

Table 4. Relative ranking of sprinklers based on kinetic energy per unit drop volume (KE_d), applied kinetic energy per unit irrigation depth (KE_a), time averaged composite specific, power kinetic energy parameters. Ranking is from highest to lowest parameter value with 1 being the highest.

Sprinkler	KE_d	KE_a	Specific Power
High Flow Rate			
Senninger I-Wob Standard 9-groove Plate	1	3	3
Nelson R3000 Brown Plate	2	6	5
Nelson R3000 Red Plate	3	1	4
Nelson S3000 Purple Plate	4	4	2
Nelson D3000 Flat Plate	9	2	1
Low Flow Rate			
Senninger I-Wob Standard 9-groove Plate	8	9	9
Nelson R3000 Brown Plate	5	7	8
Nelson R3000 Red Plate	7	8	7
Nelson S3000 Purple Plate	6	5	6

Time averaged composite specific power for all the sprinklers used in this study are given in table 3. The relationship between average composite water application rate and average composite specific power for the five sprinklers is shown in figure 9. There is good linear relationship between the two average composite values with an $R^2 = 0.99$. This relationship was expected given that specific power is linearly related to sprinkler application rate (equation 2). The significance of the relationship shown in figure 9 is that efforts by center pivot sprinkler manufacturers to develop sprinklers with greater wetted radius to reduce composite water application rates has also reduced specific power applied. The relationship also shows that some relatively large drops from center pivot sprinklers that are needed to increase wetted radius and reduce composite application rate do not necessarily result in greater transfer of kinetic energy to the soil. 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, overall kinetic energy applied will not be affected.

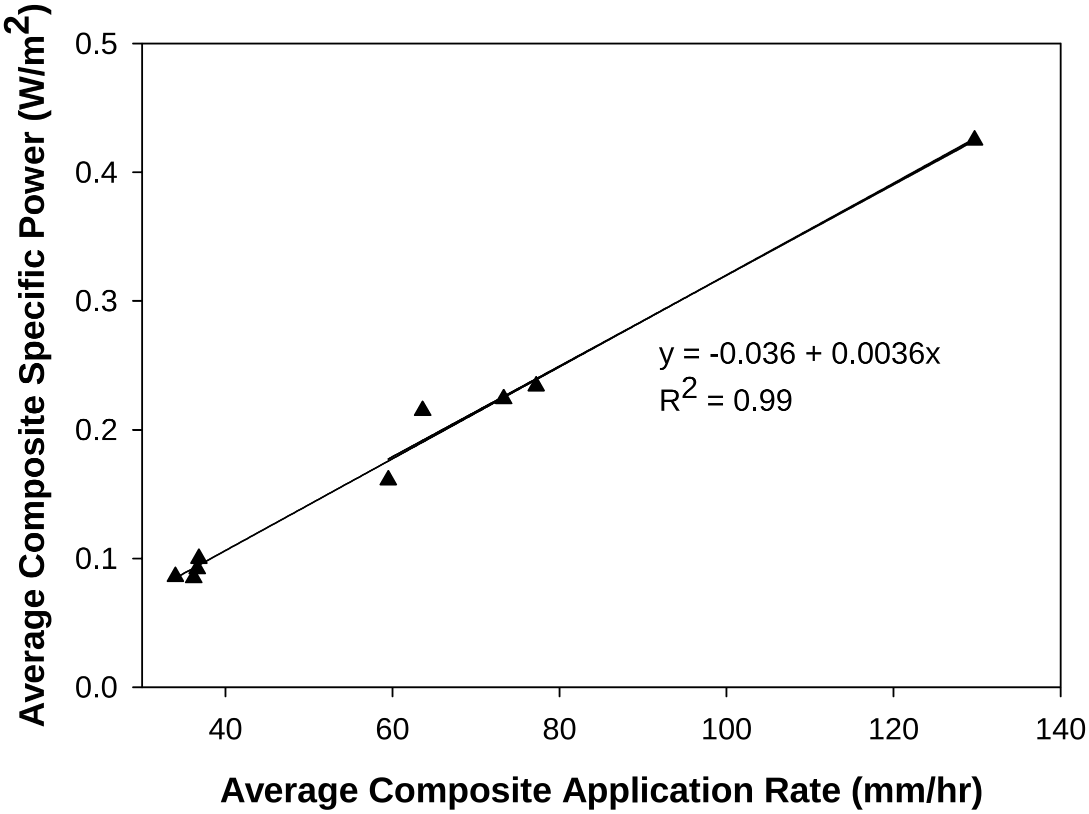

Figure 9. Relationship between average composite application rate and average composite specific power for the sprinklers used in the study.

The relative ranking of all the sprinklers used in the study based on time averaged composite specific power from highest to lowest is also given in table 4. Spearman's rank correlation coefficient between KE_a and time averaged composite specific power is 0.85 and significant ($p = 0.004$) meaning that KE_a and time averaged composite specific power are closely related as was expected since composite specific power is used to calculate kinetic energy applied. Correlations between average composite specific power and KE_a and runoff and soil erosion from sprinkler irrigation need to be investigated to determine which parameter best represents the effect sprinkler drops have on soil surface sealing and soil particle detachment and transport.

Conclusions

Area weighted kinetic energy per unit drop volume has traditionally been used in the literature to characterize kinetic energy transferred to a bare soil by sprinkler irrigation. Sprinkler specific power defined as the rate at which kinetic energy is transferred to the bare soil surface was used to calculate kinetic energy transferred to the soil by center pivot irrigation sprinklers. Kinetic energy transferred to the soil by five common center pivot sprinklers for a specific flow rates and lateral spacing was calculated based on measured drop size and velocity. The results demonstrated that area weighted kinetic energy per unit drop volume used to characterize sprinkler kinetic energy is not an indictor of kinetic energy applied to the soil under center pivot irrigation. Sprinklers with the smallest drop sizes do not necessarily transfer the least kinetic energy per unit depth of water applied. Conversely, sprinklers with the largest drop sizes do not necessarily transfer the greatest kinetic energy to the soil. Conventional thought that sprinkler drop size alone determines kinetic energy transferred to the soil is incorrect.

Acknowledgements

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