APPLICATION RATES FROM CENTER PIVOT IRRIGATION WITH CURRENT SPRINKLER TYPES

D. C. Kincaid

ABSTRACT. *Center pivot sprinkler irrigation is increasing in popularity in the United States due to the low labor requirement and ability to irrigate large fields. The main problem associated with pivots continues to be the inherently high application rates and tendency for runoff and erosion on medium- and fine-textured soils and rolling topography. Recently developed sprinklers or spray heads can produce high application uniformity with controlled drop sizes and medium sized pattern widths at medium to low pressures. A method is presented to predict the average and peak application rates at any point along a center pivot lateral for a particular type of sprinkler. The method can be incorporated with infiltration and center pivot design models to predict when runoff might occur. A computer program is available to aid in the design process and compare alternative configurations.*

Keywords. *Sprinkler irrigation, Spray irrigation, Center pivot irrigation, Water application rate, Rainfall intensity.*

Center pivot irrigation systems have become the irrigation method of choice for much of the United States, particularly in the Pacific Northwest where medium–textured soils and rolling topography dominate the landscape. Surface irrigated areas are gradually being converted to sprinkler irrigation, primarily center pivots, due to labor and water quality concerns. The 1999 Irrigation Survey (*Irrigation Journal,* 2000) found that nearly one-third of the irrigated land in the United States was irrigated by center pivots. The main problem associated with center pivot irrigation continues to be potential runoff due to the high application rates inherent with traveling laterals. Several authors have discussed the importance of application rates in relation to soil water infiltration rates and surface storage capacity in the design and evaluation of center pivot systems (Kincaid et al., 1969; Addink et al., 1980; Pair et al., 1983; Allen, 1990; Heermann, 1990; Kincaid et al., 1990; Keller and Bliesner, 1990; DeBoer et al., 1992). New types of sprinklers or spray heads have been developed which can produce high application uniformity with controlled drop sizes and medium-sized pattern widths at medium or low pressures (Kincaid et al., 2000; DeBoer et al., 2000). The objective of this work was to present a method to predict the average and peak water application rates at any point along a center pivot lateral for a particular type of sprinkler and to discuss ways to reduce or minimize peak application rates.

DEFINITIONS AND EQUATIONS

Application rate under a traveling sprinkler lateral may be described in terms of average rate, peak rate, and instantaneous rate. The "average rate" is defined as the flow rate per unit wetted area of the spray pattern and can be calculated from the discharge rate per unit length of lateral and the total pattern width or pattern radius of the sprinkler. The peak rate used here is the approximate high point of the averaged or "smoothed" application pattern from overlapping sprinkler patterns across the lateral. Higher instantaneous rates can occur for short time periods due to concentration of sprays from several sprinkler jets, or from grooved, nonrotating plates, but these rates are difficult to quantify and will not be discussed here.

The application rate pattern is herein described by the trapezoidal shape shown in figure 1. The trapezoidal pattern is defined by a shape factor, r, the ratio of peak to average rate, varying from r = 1 (rectangular), to r = 2 (triangular).

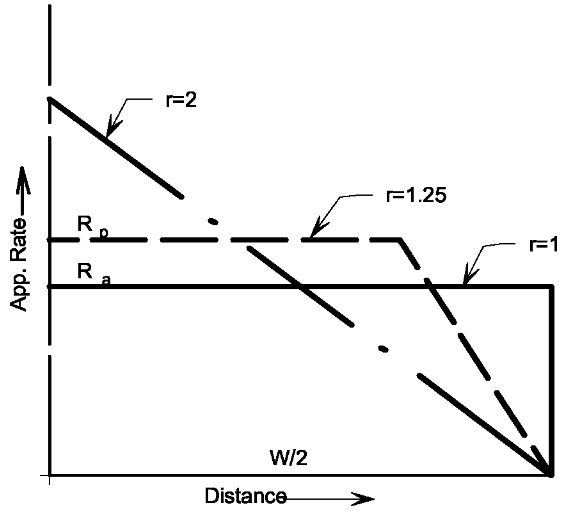

Figure 1. Definition sketch of an application rate pattern under a traveling lateral.

Article was submitted for review in November 2004; approved for publication by the Soil & Water Division of ASAE in February 2005. Presented at the 2004 ASAE Annual Meeting as Paper No. 041005.

Manufacturer's names are given for information of the reader and do not imply any endorsement or preferential treatment of the product listed by the USDA-ARS. The author is **Dennis C. Kincaid, ASAE Member Engineer,** Agricultural Engineer, USDA-ARS, Northwest Irrigation and Soils Research Lab, 3793 N 3600 E., Kimberly, Idaho 83341-5076; phone: 208-423-6503; fax 208-423-6555; e-mail: kincaid@nwisrl.ars.usda.gov.

Equations for computing discharge and application rates along a center pivot lateral have been presented by the previously-noted authors and are given here in different forms. The discharge per unit length at a point along a center pivot lateral can be determined by:

$$q_L = 0.0000727\ Q\ X_p \qquad (1)$$

where q_L is flow per unit length [L s^{-1}m^{-1} (1 L s^{-1}m^{-1}= 4.83 gpm /ft)], Q is the system gross capacity [mm/day (1 mm/day = 0.116 L s^{-1}ha^{-1} = 0.74 gpm/acre)], and X_p is the distance from the pivot (m).

Similarly, for a linear traveling lateral, q_L is constant and can be determined by:

$$q_L = 0.0000116\ Q\ X_t \qquad (2)$$

where X_t is the travel distance of the lateral (m).

In practice the gross capacity, Q, should be adjusted to allow for expected down time of the lateral and application efficiency. The average application rate can then be determined by equation 3 or 4.

$$R_a = 3600\ q_L/W \qquad (3)$$

$$R_a = 0.26\ Q\ X_p/W \qquad (4)$$

where R_a is the average application rate (mm/h), and W is the pattern width (m).

The ratio of the peak rate to the average rate is defined as:

$$r = R_p\ /R_a,\ (1 < r < 2) \qquad (5)$$

where R_p is peak rate (mm/h).

The pattern width for no-wind conditions can be obtained from manufacturer's performance data, or estimated by the following method. Kincaid (1982) presented a method for estimating the pattern radius (or diameter) for single-nozzle sprinklers, using the nozzle jet momentum as a parameter. The momentum parameter is defined as:

$$M = q_n\ P^{\ 0.5} \qquad (6)$$

where q_n is nozzle flow (L/s), and P is nozzle pressure (kPa).

A relationship for pattern width for spray heads incorporating the momentum parameter will be presented later.

PROCEDURES

Field tests were conducted to measure application rate patterns under a stationary lateral. The collector layout relative to the lateral is shown in figure 2. The lateral consisted of an aluminum boom with five equally spaced (3.4-m) bottom outlets. This spacing was found to provide complete overlap of spray patterns (on the collector area) with five identical spray heads for the devices tested, and produced high uniformity (see results). While smaller spacings are typically used on the outer portion of center pivots, the use of smaller spacings would have required more heads and would not have changed the pattern width or shape for a particular test. The boom was mounted on a stand so that it could be adjusted in elevation from 1 to 3.5 m above the ground surface. The sprinkler/spray heads were attached below the lateral boom and a pressure regulator was placed directly upstream from each head. Water was supplied to the center of the boom.

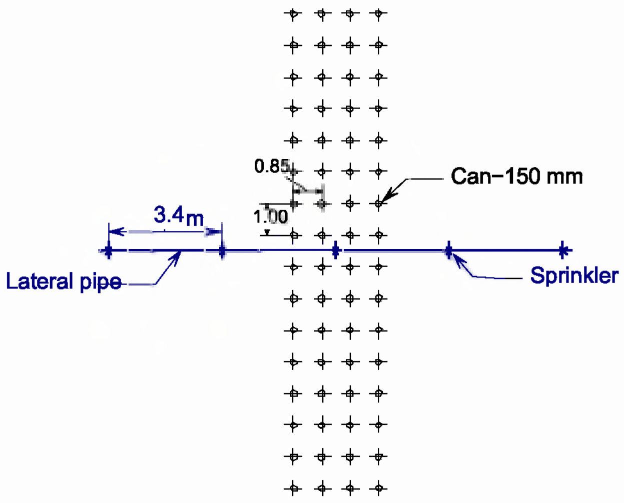

Figure 2. Field setup for measuring application rate patterns from a sprinkler lateral.

The spray collectors were 150 mm diameter by 150 mm tall, white-painted metal cans. Four rows of collectors were placed perpendicular to the lateral and spaced at ¼ of the 3.4-m sprinkler spacing, and at a spacing of 1 m within each row. The cans were placed on leveled metal plate bases. A sufficient number of collectors were placed on each side of the lateral to measure the complete pattern cross section. Tests were conducted in a large grassed area with the grass mowed to about 100 mm. To ensure complete overlap of spray patterns on the collectors, tests were run when wind direction was estimated to be within 20° of perpendicular to the lateral. Test durations ranged from 30 to 40 min. Application depths were measured by pouring the water from a catch can into a calibrated 32-mm diameter cylinder. Collectors were emptied within 15 min of the cessation of the test. Windspeed was measured with a chart-recording anemometer at a height of 2 m above the collectors.

The spray devices tested are given in table 1. Nozzle sizes of 4.76 and 6.35 mm (0.19 and 0.25 in.) were used with nozzle pressures of 103 to 207 kPa (15 to 30 psi). Nozzle mounting heights of 1.2 to 2.9 m (4 to 9.5 ft) were used. The Nelson Spray I head (Nelson Irrigation Corp., Walla Walla, Wash.) is an older style fixed-plate spray head. The R3000

Table 1. Sprinkler/spray devices tested.

Manufacturer	Device Type	Plate	Trajectory Angle (°)
Nelson	Spray I	Smooth, concave	6
	R3000	Green 4–groove	8
		Red 6–groove	12
		Orange	Various
		Brown	Various
	S3000	Red 6–groove	12
		Purple 6–groove	20
		Yellow	21
		Green	
	N3000 Nutator	Blue	
Senninger	i–wob	Black Standard 9–groove	24
		Blue Low–angle 9–groove	12
		White Low–Angle 6–groove	16

(rotator) uses a slowly rotating plate, while the S3000 uses a rapidly spinning plate, usually with four to six main grooves and various groove shapes and trajectories. The Nelson N3000 (Nutator) and Senninger i-wob sprinklers (Senninger Irrigation Inc., Orlando, Fla.) are oscillating-plate devices with six to nine grooves in which the jet passes through one or two grooves at a time. These were mounted on 1-m flexible-hose drops as recommended by the manufacturers. Spray heads with multiple fixed-groove nonrotating plates were not tested because they produce "point applications" which are difficult to measure with catch cans.

RESULTS AND DISCUSSION

Table 2 lists the main results from each individual field test, including the nozzle/plate configuration, pressure, mounting height, average windspeed, measured pattern width (average of the width from four can rows), average rate, and Christiansen uniformity. The ratio of predicted to measure pattern width is explained below. An example of the rate patterns from one test is shown in figure 3. The uniformity (CU) values were calculated by integrating each row of collector data to obtain an average rate (relative application depth) for each row, and using these four values to calculate the "Christiansen uniformity" (ASAE Standard S436.1). The high CU values indicated that the nozzle spacing used here was not excessive. There was no significant difference in uniformity between the different devices. Application uniformity measured under commercial systems will usually be lower than measured here, because of pressure variability, nozzle size changes, etc., over longer lengths of lateral, but average pattern width should be relatively insensitive to changes in spacing and uniformity.

The main purpose of the field tests was to measure spray pattern width and shape under wind conditions and compare the widths with those measured by the manufacturers under no-wind conditions. Data was obtained from the manufacturer's web sites (nelsonirrigation.com, senninger.com) and is readily available. The mounting height of the deflection plate is a significant parameter affecting the pattern width. The rational is that the pattern width should be proportional to both the jet momentum and the mounting height. Several forms of the relationship were evaluated, and the following form (eq. 7) was found to give the best predictions when fitted to manufacturer's data. Pattern width as a function of the nozzle flow, pressure, and mounting height:

$$W = a\,(H^c\,M)^b \qquad (7)$$

where H is mounting height (m), M is the momentum parameter from equation 6, and a, b, c, are empirical coefficients determined for each spray device type. (Note: The values for a, b, and c are units dependent.)

The coefficients a, b, c in equation 7 were optimized (using an Excel spreadsheet) by plotting values of (H^cM) versus W (c = 1 initially) and fitting a power function to the data points to determine values of a and b. Then, c was adjusted by trial and error to maximize the R^2 value of the regression. An example of the regression analysis for one head/plate combination is depicted in figure 4.

The coefficient values resulting from the regression analysis of manufacturer's data for several different spray device and plate combinations are given in table 3. Data for the largest nozzle sizes (>8 mm) were deleted from the analysis because the pattern widths actually tended to decrease with the largest nozzles, apparently because of plate overload. These large nozzles are rarely used in practice because of the large drop sizes produced. The smallest nozzles (<3 mm) were also excluded from the analysis. Smaller nozzles are normally used on the first span near the pivot point where application rates are low. An attempt was made to derive the pattern width constants from field pattern width data, but wind variability made the results inconsistent. The lowest R^2 values occurred with the N3000 oscillating-plate sprinkler because of the relatively narrow range of pattern widths produced, indicated by the low value of exponent b.

The coefficients from table 3 were used to calculate a predicted pattern width for each of the field tests for comparison with the field measured pattern widths. The ratio of the predicted to measured pattern widths are given in table 2. The predictions were within 10% in most cases, with no apparent bias except for the Spray-I heads, which gave larger measured widths than predicted. The largest ratios occurred for the larger windspeeds, indicating a tendency for wind to reduce the pattern width. Wind direction parallel to

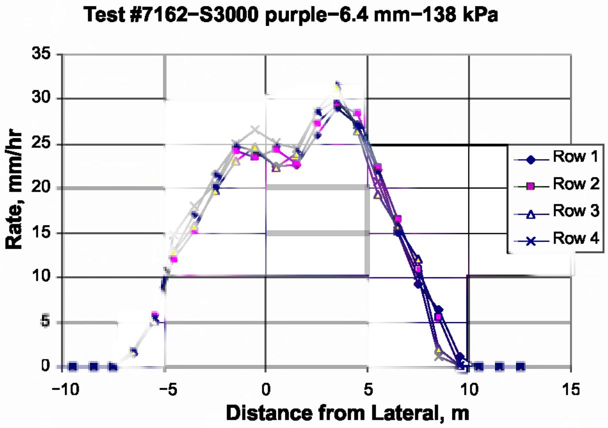

Figure 3. Application rates measured across a lateral with nozzle spacing of 3.4 m, and nozzle height of 2.44 m, wind perpendicular to lateral at 2.2 m/s. Data from four individual collector rows.

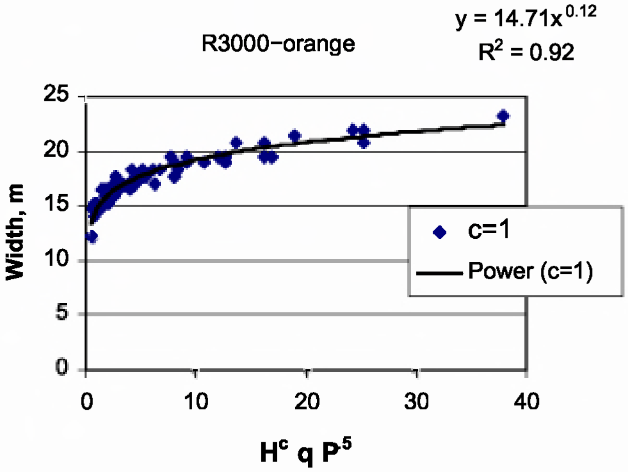

Figure 4. Example regression using manufacturer's pattern width data to obtain coefficients for equation 7.

Table 2. Field test data.

										Pattern Width			
Test Moda#	Duration (min)	Sp. Head	Plate	Nozzle (mm)	Pressure (kPa)	Height (m)	Noz. Flow (L/s)	Avg. Rate (mm/h)	Rate Ratio[a]	Meas. (m)	Pred/meas Ratio[b]	Wind (m/s)	CU[c] (%)
7221	31	Spray–I	SM CC	4.76	207	1.83	0.35	27.76	1.46	11.0	0.81	1.8	96.9
7222	30	Spray–I	SM CC	4.76	207	2.90	0.35	22.07	1.54	13.0	0.82	1.3	99.0
7235	35	Spray–I	SM CC	4.76	138	1.83	0.28	22.71	1.65	12.1	0.65	5.4	97.2
7236	30	Spray–I	SM CC	4.76	138	2.90	0.28	18.58	1.76	14.1	0.67	4.0	99.0
7161	30	S3000	purple	5.16	138	2.44	0.33	21.75	1.79	16.0	0.99	3.1	95.8
7162	27	S3000	purple	6.35	138	2.44	0.50	18.11	1.56	16.0	1.09	2.2	99.1
7303	35	S3000	purple	6.35	103	2.90	0.43	23.48	1.57	16.0	1.05	1.6	99.2
7171	45	S3000	Red	6.35	103	2.59	0.43	27.99	1.30	14.0	1.10	1.8	97.7
7191	36	S3000	Red	4.76	103	2.59	0.24	18.74	1.24	12.1	1.15	3.1	96.9
7192	45	S3000	Red	4.76	103	2.96	0.24	17.37	1.42	14.0	1.01	3.4	99.0
7211	40	S3000	Red	4.76	207	2.90	0.35	18.49	1.47	15.1	1.06	1.8	97.9
7212	40	S3000	Red	4.76	207	1.83	0.35	20.55	1.43	14.0	1.05	1.8	95.7
7233	40	S3000	Red	4.76	103	1.83	0.24	20.64	1.47	13.1	0.99	5.8	95.5
7234	40	S3000	Red	4.76	103	2.90	0.24	14.87	1.53	15.0	0.94	5.4	96.3
7237	30	S3000	Red	6.35	103	1.83	0.43	28.90	1.51	14.0	1.03	3.6	96.4
7238	25	S3000	Red	6.35	103	2.90	0.43	24.52	1.55	16.0	0.98	2.7	98.0
8031	35	S3000	yellow	6.35	103	2.90	0.43	24.96	1.63	15.0	1.08	2.7	96.0
8032	30	S3000	yellow	6.35	103	1.83	0.43	27.45	1.64	14.0	1.05	3.1	97.6
8201	30	R3000	orange	4.76	207	1.22	0.35	18.15	1.58	16.1	1.14	3.1	99.1
8202	30	R3000	orange	4.76	207	2.74	0.35	14.20	1.63	19.0	1.06	2.7	97.9
8203	30	R3000	orange	6.35	138	1.22	0.50	23.05	1.58	17.0	1.10	2.7	97.0
8204	30	R3000	orange	6.35	138	2.74	0.50	18.79	1.58	20.0	1.03	2.7	98.8
8231	30	R3000	orange	6.35	103	1.22	0.43	24.48	1.53	16.0	1.12	3.6	98.2
8232	30	R3000	orange	6.35	103	2.74	0.43	19.85	1.56	19.0	1.04	3.6	96.8
8233	30	R3000	Brown	6.35	103	1.22	0.43	26.88	1.70	15.0	1.14	3.1	97.1
8234	30	R3000	Brown	6.35	103	2.74	0.43	21.52	1.74	18.0	1.05	3.1	99.5
8241	30	R3000	Brown	4.76	138	1.22	0.28	17.11	1.82	17.0	0.98	1.3	98.7
8242	30	R3000	Brown	4.76	138	2.74	0.28	13.96	1.88	19.0	0.96	1.8	98.4
8263	30	R3000	Brown	6.35	138	1.22	0.50	29.18	1.58	13.0	1.35	5.8	97.2
8264	30	R3000	Brown	6.35	138	2.74	0.50	21.02	1.81	17.0	1.14	4.5	99.2
7223	40	R3000	Red	4.76	207	2.90	0.35	14.78	1.48	18.0	0.97	1.3	99.4
7224	40	R3000	Red	4.76	207	1.83	0.35	17.00	1.43	16.0	1.00	1.3	98.1
7231	35	R3000	Red	4.76	103	1.83	0.24	19.55	1.43	14.1	1.03	4.5	93.6
7232	35	R3000	Red	4.76	103	2.90	0.24	16.56	1.60	16.0	0.98	5.8	98.4
8261	30	R3000	Green	6.35	138	1.22	0.50	31.63	1.30	13.0	1.33	4.5	94.3
8262	30	R3000	Green	6.35	138	2.74	0.50	22.22	1.61	17.0	1.16	4.9	98.2
7261	40	R3000	Green	4.76	103	1.83	0.24	17.50	1.11	16.0	1.04	2.2	95.9
7262	42	R3000	Green	4.76	103	2.90	0.24	13.24	1.23	19.0	0.94	1.3	95.7
7281	40	R3000	Green	4.76	207	2.90	0.35	14.18	1.28	20.0	0.97	3.1	98.6
7282	40	R3000	Green	4.76	207	1.83	0.35	18.47	1.20	17.0	1.06	3.1	95.9
8271	30	N3000	Green	6.35	138	1.83	0.50	26.44	1.63	15.0	1.02	3.1	99.0
8272	30	N3000	Green	4.76	138	1.83	0.28	18.97	1.65	15.1	0.97	2.7	98.5
8273	30	N3000	Green	6.35	103	1.83	0.43	27.03	1.59	15.0	1.00	2.5	98.7
8274	30	N3000	Blue	6.35	103	1.83	0.43	31.97	1.60	13.0	1.09	1.8	97.1
7291	40	i–wob	Black	4.76	207	1.83	0.34	19.23	1.83	16.0	0.98	2.2	99.5
7292	40	i–wob	Black	4.76	138	1.83	0.28	19.20	1.69	15.0	0.99	1.8	98.9
7301	30	i–wob	Black	6.35	138	1.83	0.51	27.57	1.40	15.0	1.07	1.1	99.7
7302	35	i–wob	Black	6.35	103	1.83	0.44	26.37	1.42	15.0	1.03	1.3	98.1
8053	33	i–wob	Blue	6.35	103	1.83	0.44	28.32	1.30	14.0	1.04	3.1	95.0
8054	40	i–wob	Blue	4.76	103	1.83	0.24	19.08	1.38	13.1	1.03	2.7	99.0
8061	35	i–wob	Blue	4.76	138	1.83	0.28	18.80	1.55	15.0	0.93	2.2	99.4
8062	35	i–wob	Blue	4.76	207	1.83	0.34	20.16	1.52	15.0	0.98	2.2	98.6
8063	30	i–wob	Blue	6.35	138	1.83	0.51	30.16	1.28	14.0	1.08	2.2	97.5
8191	30	i–wob	White	6.35	138	1.83	0.51	28.08	1.27	15.0	1.03	1.3	98.1
8192	30	i–wob	White	4.76	207	1.83	0.34	18.76	1.54	16.0	0.95	1.3	99.1

[a] Rate ratio = ratio of peak to average application rate.

[b] Pred/meas = ratio of predicted (eq. 7) to measured pattern width.

[c] Christiansen uniformity coefficient (ASAE Standard S436.1)

Table 3. Pattern width constants for use with equation 7 and peak rate ratio.

Device	Plate	a	b	c	R^2	Rate Ratio (r)
Spray–I	Smooth	4.35	0.31	1.2	0.97	1.6
i–wob	Standard	12.2	0.12	0.8	0.93	1.6
i–wob	Lowangle 9–groove	11.4	0.12	0.9	0.85	1.4
i–wob	Lowangle 6–groove	12.0	0.11	0.9	0.85	1.4
A3000	Maroon	11.4	0.12	1.3	0.84	1.5[a]
R3000	Green	13.6	0.12	1.3	0.91	1.3
R3000	Red	11.3	0.15	1.2	0.88	1.5
R3000	Orange	14.7	0.12	1.0	0.92	1.6
R3000	Brown	14.4	0.10	1.2	0.85	1.8
S3000	Red	9.9	0.18	1.0	0.93	1.4
S3000	Purple	10.1	0.22	0.8	0.93	1.6
S3000	Yellow	9.9	0.18	1.2	0.94	1.6
S3000	Gray	9.8	0.25	0.8	0.94	1.5[a]
N3000	Green	12.2	0.08	1.8	0.78	1.6
N3000	Blue	10.6	0.08	3.5	0.82	1.6

[a] Preliminary estimate for r.

the lateral also tends to reduce the pattern width (Addink et al., 1980; Keller and Bliesner, 1990), although this effect was not measured. Thus, it appears that equation 7 will predict pattern width and application rates within 10% for moderate wind conditions, an acceptable accuracy considering the difficulty of predicting infiltration rates.

Also listed (table 3) are average peak rate ratios (eq. 5) derived from field test data (table 2). The "peak rate" used here was the average of the three highest contiguous rates across the pattern. True "instantaneous rates" can be higher than peak rate but are difficult to measure. For design purposes, it is usually sufficient to use average rate, but if no surface storage is available, peak rate should be used.

Increasing the mounting height can reduce application rates, but this increases wind drift. A dual-height system, where spray heads are mounted alternating between two different heights, reduces interference between adjacent sprays and may be beneficial when wind is blowing perpendicular to the lateral. Two tests at nearly the same windspeed were combined to illustrate this effect and the results are shown in figure 5. The lower elevation sprays drift less than the higher sprays, and the combined pattern has about the same width as the high sprays, with a lower peak rate than the lower height sprays. Wind direction is perpendicular to the lateral approximately 50% of the time on a full circle pivot. However, on a linear traveling lateral oriented perpendicular to prevailing winds, this configuration could be effective most of the time. Dual-height mounting is a low-cost means of reducing spraydrift while maintaining a relatively wide pattern.

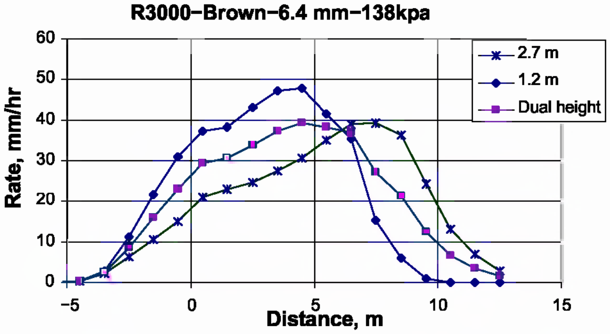

Figure 5. Measured application rate patterns for dual mounting heights in a 4.5-m/s wind.

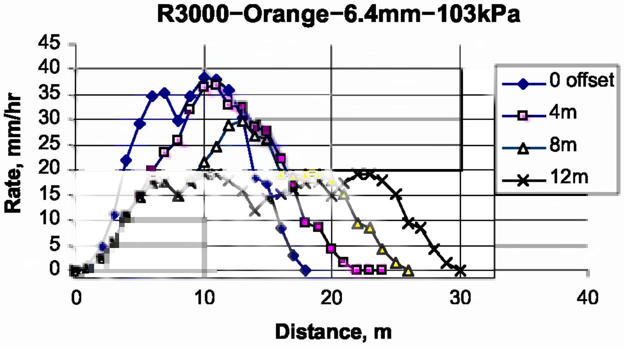

Figure 6. Effect of horizontal offset on measured application rates.

Horizontal offsets reduce application rates by widening the pattern as shown in figure 6. In this method, spray heads are alternately offset on either side of the lateral by means of rigid, cantilevered pipes called spray booms. The total offset distance is simply added to the spray pattern width when calculating the average application rate. The peak rate ratio can be considered constant for moderate offsets. The greatest reduction in the peak rate occurs when the total offset reaches about 70% of the pattern width. The addition of offset booms is expensive per spray head, but can be cost effective for the outer portion of a center pivot lateral where each unit length of lateral covers a large area, and application rates are highest.

MODEL APPLICATION

A nozzle sizing equation is needed to complete the design model. An equation that predicts nozzle size as a function of required flow and pressure (fitted to Nelson and Senninger nozzle performance data) is:

$$d_n = 30.22\, q_n^{\,0.495} / P^{\,0.248} \qquad (8)$$

where d_n is nozzle diameter (mm).

An example calculation (table 4) illustrates the use of the equations in the design of a center pivot. A system capacity of 9 mm/day was selected, and calculations were done at three distances from the pivot representative of the inner, middle, and outer portions of a typical pivot lateral. The sprinkler/plate types, and the nozzle spacings were arbitrarily selected to keep the nozzle sizes within the desired 3- to 8-mm range. The nozzle flow, nozzle size, pattern width, and application rates were calculated using the previous equations and coefficients. Changing the nozzle spacing from 3 to 2 m at the 400-m distance had a minimal effect on application rate. The effect of adding horizontal offsets on the outer portion of the lateral is also demonstrated.

A computer program has been developed to aid in the process of selecting sprinkler model, pressure, spacing, etc., sizing nozzles and comparing alternative configurations. This program, called PIVNOZ, can be obtained by contacting the author or Richard Dinges at rdinges@nwisrl.ars.usda.gov.

Table 4. Example application rate calculations for a center pivot with a gross capacity of 9 mm/day, nozzle pressure of 138 kPa, and nozzle height of 3 m.

Distance from Pivot (m)	Nozzle Spacing (m)	Sprinkler–plate	Nozzle Flow (L/s)	Nozzle Size (mm)	Pat. Width (m)	Avg. Rate (mm/h)	Peak Rate (mm/h)
40	5	R3000–Green	0.13	3.26	17.0	5.5	7.2
200	3	R3000–Orange	0.39	5.62	20.1	23	37
400	3	R3000–Orange	0.79	7.92	21.9	43	69
400	2	R3000–Orange	0.52	6.48	20.9	45	72
400	2	R3000–Orange	0.52	6.48	30.9[a]	31	50

[a] Includes 10–m horizontal offset booms

CONCLUSIONS

An equation was developed to predict spray pattern width as a function of nozzle flow, pressure, and mounting height for a specific type of spray device. This equation, combined with a nozzle sizing and flow equations and the coefficients from table 3 provide a means to predict the average and peak application rate at any location along a center pivot or traveling lateral given the device and plate type, mounting height, spacing, and pressure. These relationships should enable designers to better analyze the tradeoffs between nozzle pressure, spacing, and mounting height, as well as to compare different types of spray devices and alternative mounting configurations.

ACKNOWLEDGEMENT

The author wishes to thank Richard A. Dinges, research technician, for his help in collecting and analyzing the field data, and computer programming.

REFERENCES

Addink, J. W., J. Keller, C. H. Pair, R. E. Sneed, and J. W. Wolfe. 1980. Design and operation of sprinkler systems. In *Design and Operation of Farm Irrigation Systems*, ed. M. E. Jensen, 621-660. St. Joseph, Mich.: ASAE.

Allen, R. G. 1990. Applicator selection along center-pivots using soil infiltration parameters. In *Visions of the Future*, 549-555. St. Joseph, Mich.: ASAE.

ASAE Standards, 48th Ed. 2001. S436.1. Test procedure for determining the uniformity of water distribution of center pivot and lateral move irrigation machines equipped with spray or sprinkler nozzles. St. Joseph, Mich.: ASAE.

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

DeBoer, D. W., M. J. Monnens, and D. C. Kincaid. 2000. Rotating-plate sprinkler spacing on continuous-move irrigation laterals. In *National Irrigation Symposium; Proc. of the 4 th Decennial Symposium*, 115-122. St. Joseph, MI.: ASAE.

Heermann, D. F. 1990. Center pivot design and evaluation. In *Visions of the Future*, 564-570. St. Joseph, Mich.: ASAE.

Irrigation Journal. 2000. 1999 Annual irrigation survey. *Irrigation Journal* Jan.-Feb. 2000.

Keller, J., and R. D. Bliesner. 1990. *Sprinkle and Trickle Irrigation.* New York: Chapman and Hall.

Kincaid, D. C., D. F. Heermann, and E. G. Kruse. 1969. Application rates and runoff in center-pivot sprinkler irrigation. *Transactions of the ASAE* 12(6): 790-794, 797.

Kincaid, D. C. 1982. Sprinkler pattern radius. *Transactions of the ASAE* 25(6): 1668-1672.

Kincaid, D. C., I. McCann, J. R. Busch, and M. Hasheminia. 1990. Low pressure center pivot irrigation and reservoir tillage. In *Visions of the Future*, 54-60. St. Joseph, Mich.: ASAE.

Kincaid, D. C., B. A. King, and D. W. DeBoer. 2000. Sprinkler packages and their configurations for center pivot irrigation. In *National Irrigation Symposium; Proc. of the 4 th Decennial Symposium*, 109-114. St. Joseph, Mich.: ASAE.

Pair, C. H., W. H. Hinz, K. R. Frost, R. E. Sneed, and T. J. Schiltz. 1983. *Irrigation,* 5th Ed. Arlington, Va.: The Irrigation Association.