APPLICATION RATES AND UNIFORMITY UNDER CENTER-PIVOT SPRINKLER IRRIGATION SYSTEMS USING SPRAY NOZZLES

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Uniformity of water application in circular and radial directions under various center-pivot irrigation systems using spray nozzles was recorded in the field on farmer-operated systems. For the eight systems studied, the average application was 15.2 mm and the Christiansen uniformity coefficient values were all above 80%. A computer model was developed to simulate field water application distributions using single sprinkler distributions that had been determined in the laboratory. These distributions were used to predict potential runoff rates under various operating conditions. Simulation showed that it is possible to obtain a high uniformity coefficient with any spray pattern provided the nozzles are spaced properly; however, the result may be an application rate that is great enough to produce runoff.

INTRODUCTION

As the cost of energy increased, many sprinkler irrigation farmers purchased low-pressure (under 300 kPa) center-pivot systems that use spray nozzles. The radius of throw for these nozzles is only 25–35% of that for conventional high-pressure sprinklers, and the pumping rate for either a low-pressure or high-pressure system, covering the same area, must be approximately the same. Therefore, the instantaneous application rate is much greater for the low-pressure system than for the high-pressure system. This high application rate can often lead to runoff and inefficient irrigation. In addition, for electrically driven machines, the distance traveled between stops by any tower of the center pivot system can be a significant fraction of the radius of throw of the spray nozzles. This may also contribute to nonuniform application of water.

The objectives of the work described here were:

(a) To determine, in the field, water application distributions and uniformities along radial and circular lines from low-pressure center-pivot systems using spray nozzles.

(b) To simulate, by means of computer modeling, field application distributions by numerically overlapping single nozzle distribution patterns obtained from laboratory tests.

(c) To use simulated distributions to calculate uniformity of application and potential runoff.

FIELD TESTS

All field tests were carried out on farmer-operated center-pivot machines on or in the vicinity of the Outlook Irrigation District in Saskatchewan. Eight electrically driven machines were tested. No hydraulically driven machines were available for testing.

Water application distributions were measured while each machine was operating under normal field conditions, except that the test periods were chosen so that the wind was relatively light. One-litre catch cans of 100 mm diameter were positioned on stands approximately 0.90 m above ground level. When determining the distributions along circular arcs, the cans were spaced 0.30 m apart, while the spacing for most radial line tests was 5.0 m; however, in some instances spacings of 10.0 and 15.0 m were used. Depending upon the length of arc that was required to obtain a representative distribution, 20–50 cans were used to obtain each circular arc distribution.

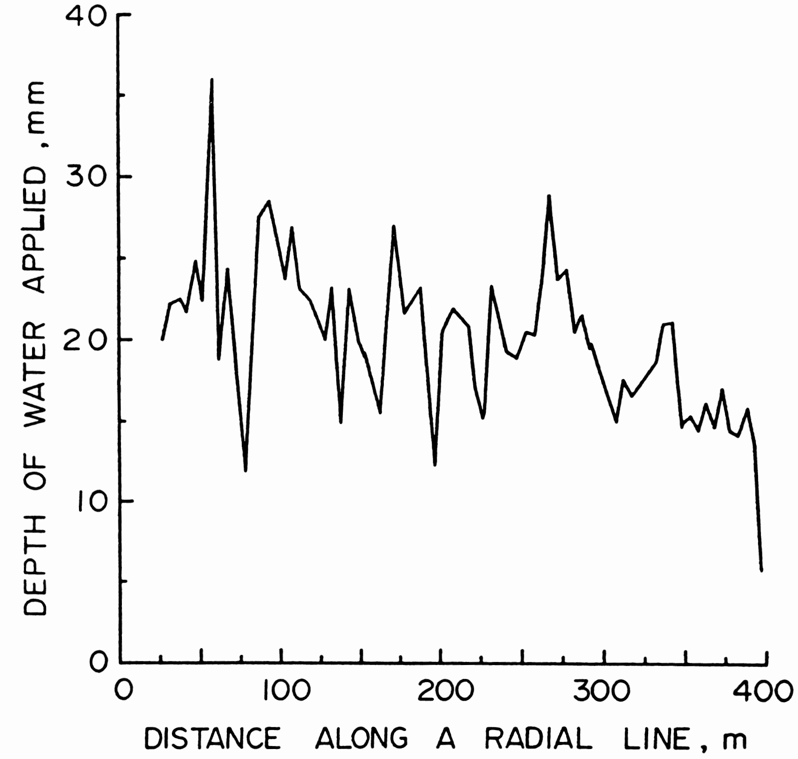

Figure 1. Example of water application distribution taken along a radial line for a center-pivot irrigation system.

Thirty-two field tests were made, eight

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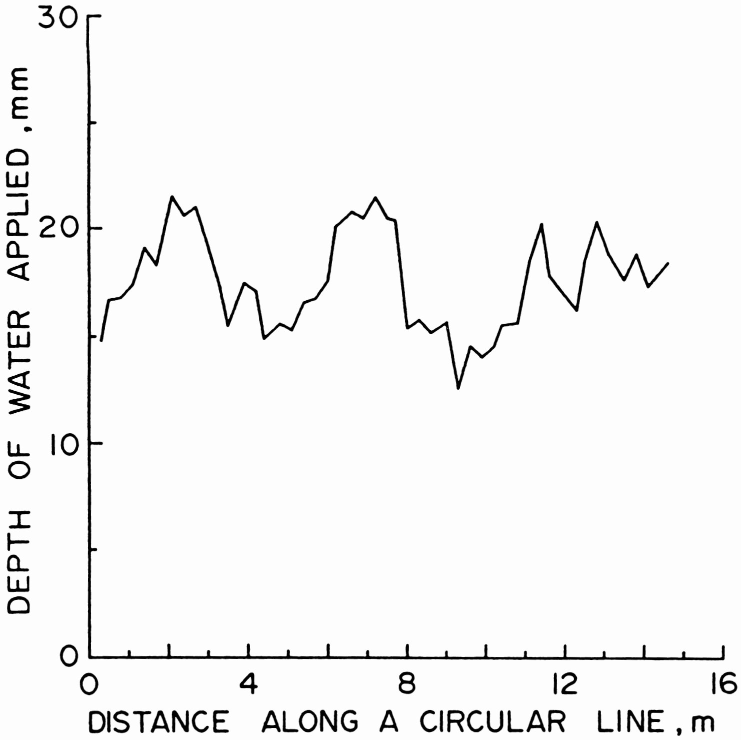

Figure 2. Example of water application distribution taken along a circular line for a center-pivot irrigation system.

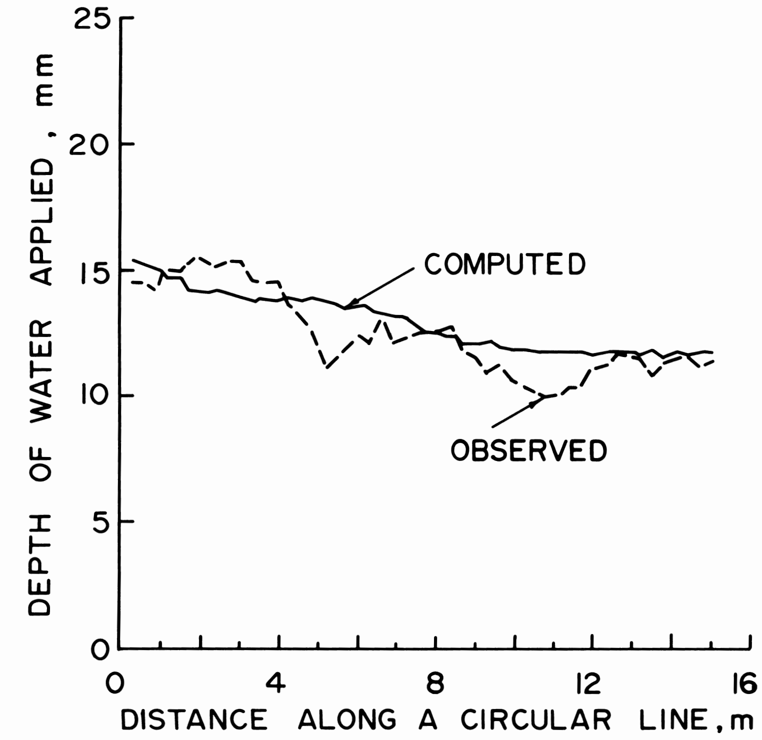

Figure 3. Observed and computed application distributions along a circular line with a nozzle height of 3.7 m, a speed of rotation 40% of full speed and a distance from the pivot of 487 m.

along radial lines and 24 along circular lines. The average depths of application for the 32 tests ranged from 9.6 to 27.9 mm, with an overall average of 15.2 mm. The Christiansen uniformity coefficients (UCC) for radial lines ranged from 82 to 88%, and for circular lines ranged from 81 to 94%. Figures 1 and 2 show examples of the distributions obtained from radial lines and circular lines, respectively.

SIMULATION OF FIELD DISTRIBUTIONS

Single-nozzle distribution tests were carried out in the laboratory to determine the water distributions from four types of spray nozzles operating at various pressures and heights above the ground surface. Type 1 nozzles were Nelson nozzles with a flat spray plate; Type 2 were Rainbird with a flat spray plate; Type 3 were Nelson with a convex spray plate; and Type 4 were Nelson with a concave spray plate. Details of these tests are given by Thooyamani (1982). Field application distributions were then simulated numerically by overlapping patterns from the laboratory tests.

Chu and Moe (1972) have shown that for a well-designed center-pivot system with a large number of nozzles, the flow rate, Q, and the pressure, P, at any point in the lateral can be defined by

$$Q = Q_0(1 - X^2) \qquad (1)$$

$$\frac{P - P_e}{P_0 - P_e} = 1 - \frac{15}{8}\left[X - \frac{2}{3}X^3 + \frac{1}{5}X^5\right] \qquad (2)$$

where Q_0 = flow rate at the pivot, P_0 = pressure at the pivot, P_e = pressure at the end of the lateral, L = length of the lateral, s = distance along the lateral from the pivot, and $X = s/L$. Equations 1 and 2 are valid only for a horizontal lateral of uniform pipe diameter.

To simulate the movement of the center pivot lateral, it was assumed that the position of the lateral line could be modeled by moving the end tower for a certain percentage of a minute and that the maximum "out-of-alignment" for any intermediate tower was 1.0 m.

A computer program was developed to calculate the time rate of application of water at any point in the field using the nozzle sizes, lateral line pressure, and lateral line position. In addition to using the single sprinkler distributions obtained in the laboratory, simulations were carried out using single sprinkler triangular and elliptical distributions with the same areal coverage and average application rate.

Distribution and Uniformity

Simulations were carried out for a number of systems using pivot rotational speeds of 10–100% of maximum speed in steps of 10%. Distributions were obtained for radial lines and for circular arcs at 30, 60 and 90% of the lateral length from the pivot. Figure 3 is an example of the simulation for a circular arc. Figure 4 shows the simulation for a radial line.

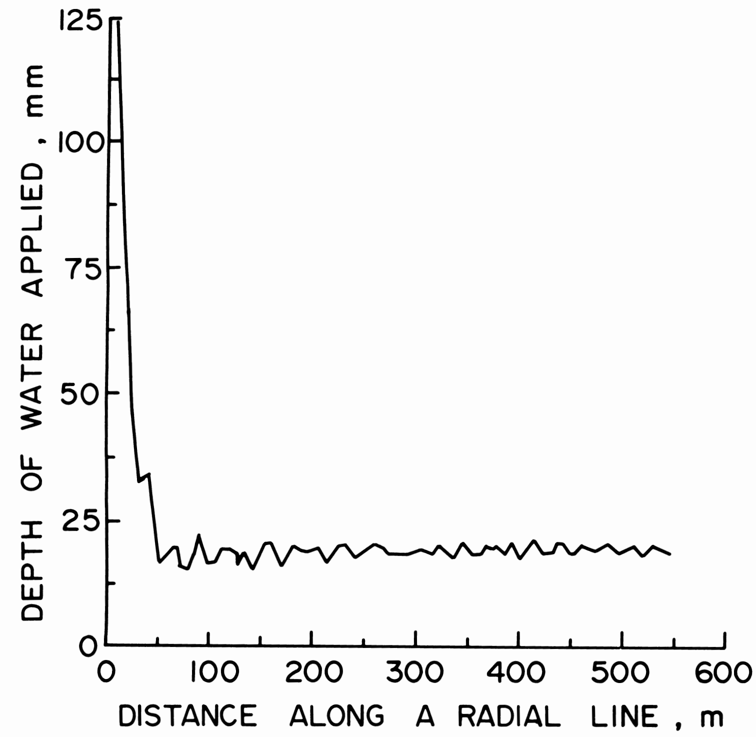

Figure 4. Predicted application distribution with nozzles operating at 3.7 m height (28.8 h per revolution at 100% speed).

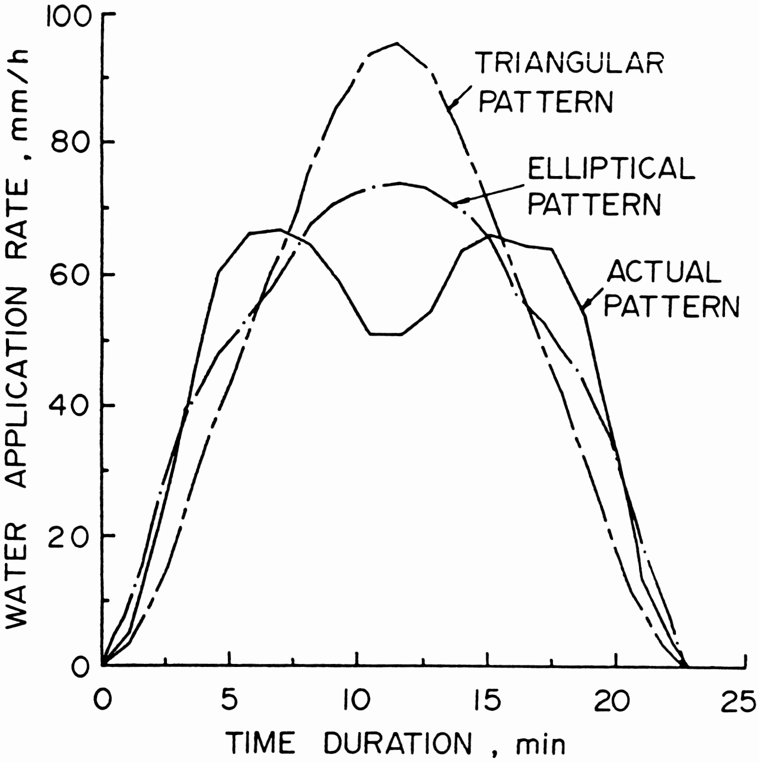

Figure 5. Predicted application rates using actual, triangular and elliptical spray patterns with a nozzle height of 3.7 m, a speed of rotation 30% of full speed and a distance from the pivot of 523 m.

Application Rates

Figure 5 shows an example of the application rate at a fixed point as simulated using actual sprinkler patterns and assumed triangular and elliptical patterns. In most cases the peak application rate for actual patterns was less than that for the triangular pattern because the actual pattern generally had a doughnut shape. The double peaks from the actual pattern generally were about the same magnitude as produced by the flatter elliptical pattern. The shape of the application rate pattern at a point is, for practical purposes, independent of the speed of rotation of the lateral. It is only the time scale that changes with speed. Figures 6 and 7 show average application rates along the lateral when the nozzles were assumed to be at two different heights, 1.2 and 3.7 m. In these cases, increasing the nozzle height from 1.2 to 3.7 m decreased the average application rates by approximately 40%.

Potential Runoff

Potential runoff is defined as the percentage of total depth of water applied, that is, applied when the application rate is greater than the soil intake rate. For simulation purposes, it was assumed that the ponded water infiltration rate for the soil could be described by the Kostiakov equation

$$I = K t^n \tag{3}$$

where I = infiltration rate under ponded conditions, (mm/h), t = time since water was first applied (h), and K and n are coefficients dependent on the soil type. As for much of the time (preferably all the time) the application rate from the sprinkler system is less than the infiltration rate, Eq. 3 must be modified to take that into account. The method used was that of Cook (1946) and Kincaid et al. (1969) in which for nonponded conditions

$$I_m = I \frac{D_p}{D_a} \tag{4}$$

where I_m = modified infiltration rate, D_p = depth of water infiltrated under ponded conditions, and D_a = depth of water actually infiltrated. Once ponding reoccurs, the infiltration rate reverts to the regular Kostiakov equation except that the time is offset by a value Δt so that

$$I = K(t - \Delta t)^n \tag{5}$$

satisfies the current infiltration rate, I_m. The rate equation that was assumed for simulation purposes was

$$I = 14.3\, t^{-0.46} \tag{6}$$

which corresponds to a medium textured soil (sandy clay loam).

Potential runoffs were calculated for a number of systems and operating speeds, for various distances from the pivot. Table I is an example for one system showing the potential runoff as a percentage of the applied depth at various points away from the pivot, and as a function of the speed of rotation of the system. The bottom line of Table I gives the percentage runoff for the

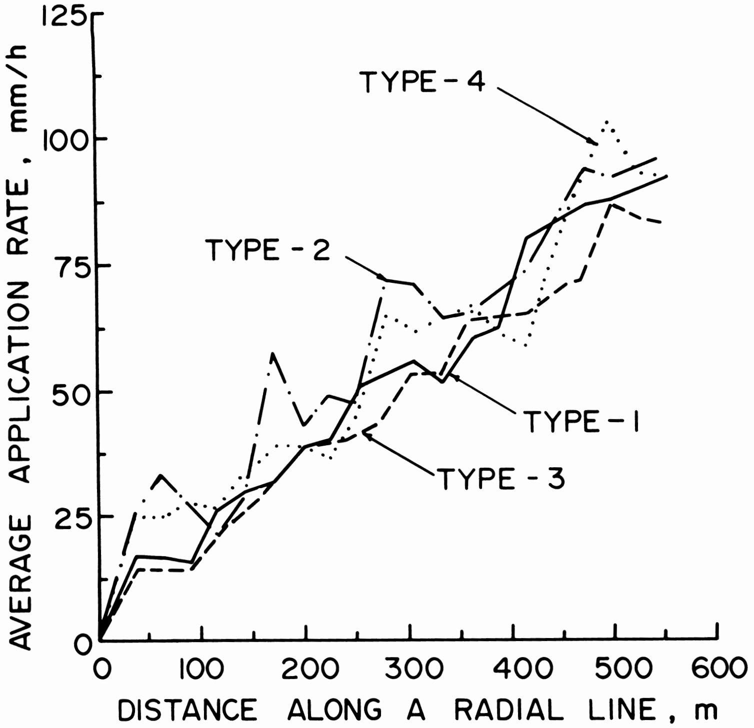

Figure 6. Predicted average application rates along radial lines for four sprinkler types with nozzles at 1.2 m height (28.8 h per revolution at 100% speed).

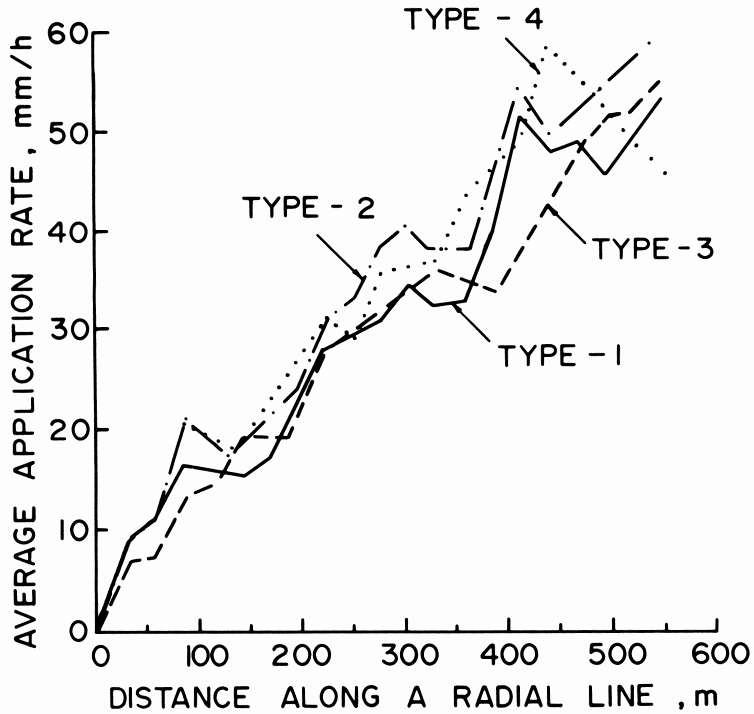

Figure 7. Predicted average application rates along radial lines for four sprinkler types with nozzles at 3.7 m height (28.8 h per revolution at 100% speed).

entire system. Figures 8 and 9 show the potential runoff at points away from the pivot for nozzles at 1.2 and 3.7 m height, respectively. It is clear that increasing the nozzle height reduces the potential runoff considerably.

DISCUSSION

As with most irrigation systems, the prime objective of operating a low-pressure center pivot system is to apply an adequate depth of water uniformly over the field with a minimum amount of runoff. The main factors that affect this objective are:

(a) system pipe size, nozzle sizes, spacing and height, and operating pressure;

(b) distribution pattern from individual nozzles;

(c) speed of rotation of machine around the field;

(d) wind;

(e) crop canopy;

(f) infiltration rate characteristics of the soil;

(g) topography; and

(h) ground surface condition (ability to pond water).

Factors (a), (b), and (c) are essentially ''hardware'' factors which can be characterized in sufficient detail by testing, so that the water application from the system can be described accurately. In some cases, topography may have an effect on this distribution if there are sufficient differences in field elevations that the pressure distribution in the lateral line is affected. However, if the topography is known, it is still possible to take that into consideration when simulating the distribution from the system.

Wind is the one factor that distorts the distribution pattern as it comes from the system, and before it reaches the crop canopy or the ground surface. Although wind has a major effect on the ground distribution it is extremely difficult to characterize the effect as the distortion depends not only on the wind speed and direction, but also on the droplet size, nozzle height and trajectory of the droplets as they leave the nozzle.

Distortion of the distribution pattern by wind can have a very marked effect on the uniformity coefficient for the distribution. This is especially so under prairie conditions. Although field tests and simulations may indicate high uniformity, it is possible that on an entire field basis, say a 60-ha circle, the uniformity will be considerably less, because of the distribution pattern being distorted and shifted as the wind changes speed and direction during the time the system is making one revolution of the field. Under these conditions there may be some advantage in using small depths of application as the irrigations must be frequent and there is a reasonable probability that each time the machine is situated at a particular point in the field, the wind speed and direction will be different. Therefore, the accumulated distribution for a number of irrigations will be more uniform than for a distribution resulting from one equivalent depth irrigation. The irrigation efficiency may be relatively poor, but the overall uniformity may be

TABLE I. EXAMPLE OF SIMULATED POTENTIAL RUNOFF (%) ALONG A RADIAL LINE FOR A SYSTEM OPERATING AT VARIOUS PERCENTAGES OF CONTINUOUS OPERATING SPEED

Distance	Speed of revolution									
(m)	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
37	22.8	5.9	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
64	18.5	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
91	30.6	12.5	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0
118	25.3	8.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0
145	18.5	2.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
172	21.4	5.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
199	34.7	17.1	6.5	1.0	0.0	0.0	0.0	0.0	0.0	0.0
226	43.2	26.6	16.2	7.9	3.5	1.3	0.0	0.0	0.0	0.0
253	44.2	28.3	16.8	9.2	4.7	1.5	0.0	0.0	0.0	0.0
280	41.6	23.9	12.6	5.6	1.1	0.0	0.0	0.0	0.0	0.0
307	42.6	25.4	14.9	8.3	4.7	1.4	0.0	0.0	0.0	0.0
334	42.1	23.3	13.1	6.2	2.9	0.7	0.0	0.0	0.0	0.0
361	44.0	25.6	13.5	8.1	3.9	0.9	0.0	0.0	0.0	0.0
388	49.4	34.9	23.4	14.4	9.5	5.9	3.3	1.1	0.0	0.0
415	56.1	43.8	35.7	28.2	20.5	14.2	10.0	7.5	4.8	3.0
442	54.4	40.8	32.8	24.9	18.4	12.4	8.3	4.4	1.5	0.1
469	52.8	38.4	29.4	21.0	13.3	8.2	5.3	2.8	0.9	0.0
496	52.0	35.8	24.7	15.4	11.0	7.5	4.5	2.2	0.9	0.0
523	53.0	38.3	26.6	17.4	11.8	8.3	4.8	2.1	0.4	0.0
550	56.0	42.8	31.4	23.7	16.7	11.5	7.6	4.0	1.7	0.0
System	46.0	30.5	20.6	13.7	9.0	5.6	3.4	1.9	0.8	0.2

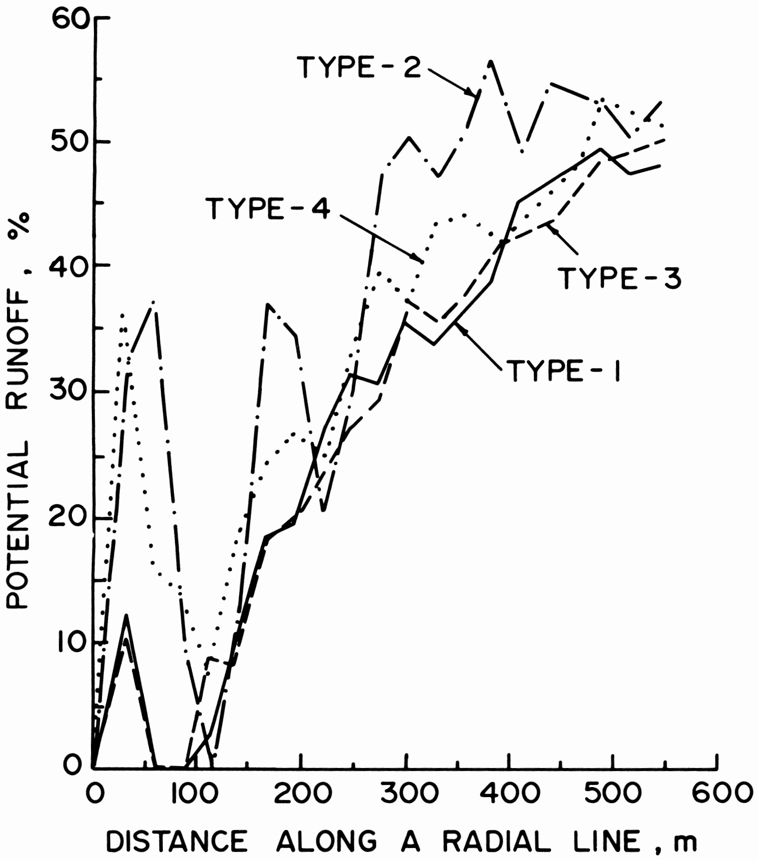

Figure 8. Potential runoff along radial lines for four sprinkler types with nozzles at 1.2 m height and 30% speed of rotation (28.8 h per revolution at 100% speed).

improved by small applications.

Once the water reaches the crop canopy there may be some additional distortion of the distribution pattern; however, from a practical standpoint, the main effect of the canopy is to intercept some of the water so that it never reaches the ground surface. Although this interception is only of the order of a few millimeters of water, it may be quite significant when only small depths of water are being applied.

Water that reaches the ground surface at some point either:

(a) infiltrates directly into the soil at that point;

(b) becomes ponded at that point and infiltrates at some later time;

(c) flows to some other point in the field and infiltrates at some later time;

(d) flows off the field entirely and is lost to drainage; or

(e) evaporates after becoming ponded somewhere in the field.

In most situations (e) can be neglected as it has little effect on the distribution. Condition (d) is generally not significant for most sprinkler systems. If it is significant, there is something radically wrong with the system and major changes must be made in its design and/or operation. Conditions (b) and (c) are first of all dependent upon the application rate and the infiltration rate characteristics, but then become very much dependent upon the topography and the surface condition.

Hart (1972) has shown that the uniformity of water infiltrating at the ground surface may be improved considerably if the redistribution within the soil profile is taken into consideration. He shows examples of a uniformity coefficient of 60% for the water distribution at the ground surface becoming 76 and 86% after redistribution in the soil for 1 and 2 days, respectively. The effect of redistribution within the soil is, of course, much dependent upon the spatial distance between above average and below average applications.

The results of the simulated tests show that good uniformity can be obtained by proper spacing of the nozzles on the lateral, but the resulting application rate may produce runoff. The application rate can be reduced by increasing the height of the nozzles but this may lead to greater wind drift losses and reduced uniformity. From the simulations it would appear that it is feasible to calculate potential runoff for a system if the infiltration characteristics of the soil are known. However, potential runoff does not take into consideration the topography and surface conditions, which are entirely site specific. Potential runoff is only a measure of the amount of water that is applied that may either pond or redistribute on the surface due to the application rate being greater than the intake rate.

SUMMARY AND RECOMMENDATIONS

The water application distributions along both radial and circular lines were determined for eight low-pressure center-pivot sprinkler systems that were operating under normal field conditions. The average application was 15.2 mm and all

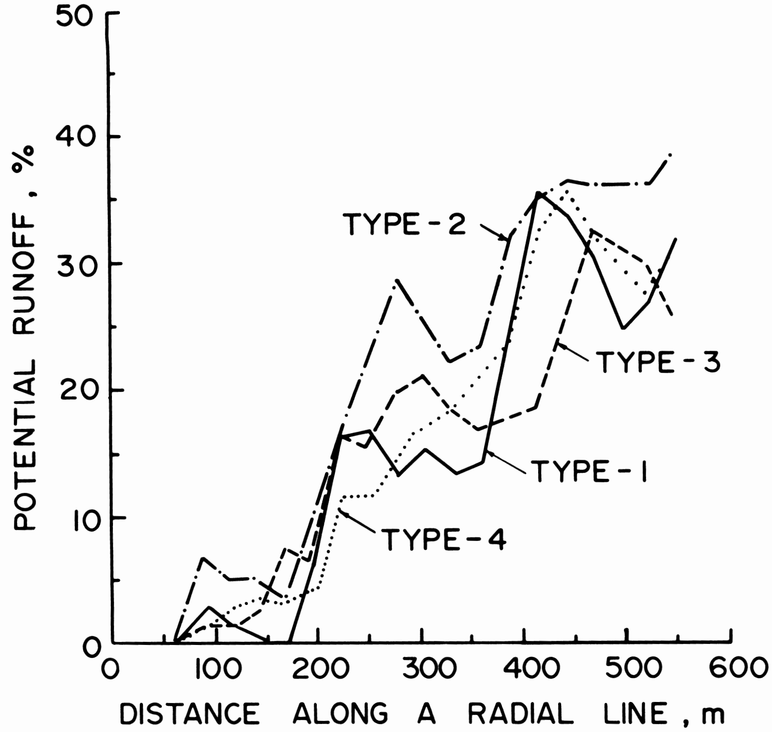

Figure 9. Potential runoff along radial lines for four sprinkler types with nozzles at 3.7 m height and 30% speed of rotation (28.8 h per revolution at 100% speed).

UCC values were above 80%.

A computer program was developed to simulate the distribution from a center-pivot system using single-nozzle distributions that had been determined in the laboratory. By assuming a particular infiltration function for the soil, it was possible to use the program to determine potential runoff for various operating conditions. Simulation showed that it is possible to obtain a high uniformity coefficient with any spray pattern provided the nozzles are spaced properly; however, the result may be an application rate that is great enough to produce runoff. The application rate can be reduced by increasing the height of the nozzles but this may result in increased losses due to wind drift. Results from the simulations showed that the application rate was essentially independent of the rotational speed of the system.

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LIST OF SYMBOLS

D_a = depth of water actually infiltrated (mm).
D_p = depth of water infiltrated under ponded conditions (mm).
I = infiltration rate under ponded conditions (mm/h).
I_m = modified infiltration rate (mm/h).
K = infiltration coefficient dependent on the soil type (mm/h^n).
L = length of the lateral (m).
n = infiltration coefficient dependent on the soil type.
P = pressure at point s (kPa).
P_0 = pressure at the pivot (kPa).
P_e = pressure at the end of the lateral (kPa).
Q = flow rate at point s (L/sec).
Q_0 = flow rate at the pivot (L/sec).
s = distance along the lateral from the pivot (m).
t = time since water was first applied (h).
X = s/L.
Δt = time offset to make I equal to I_m (h).