# Performance Characteristics of Self-Propelled Center-Pivot Sprinkler Irrigation System

**D. F. Heermann and P. R. Hein**
Assoc. Member ASAE  Assoc. Member ASAE

THE increased emphasis on labor reduction in agriculture has increased the demand for various automatic irrigation systems. Sprinkler manufacturers have developed equipment with varying degrees of automation. A recent innovation is the center-pivot system covering about one-quarter section of land.

The effectiveness of this equipment can be evaluated using established guidelines such as the ASAE recommendations (1)* covering minimum requirements for the design, installation and performance of sprinkler irrigation equipment. One of these recommendations specifies that the application rate should not cause runoff to occur during the normal operation of the sprinkler system. A second is that a uniform distribution of depth of application be achieved. For practical purposes this is done by limiting the pressure drop on a lateral to 20 percent of the higher pressure. An excessive pressure difference would cause considerable nonuniformity in water application with a conventional system. However, the uniformity of application depth with the center-pivot irrigation system is not a function of pressure distribution only, but is regulated by increasing the sprinkler size and discharge proportionately to the increase in area as the radial distance from the pivot increases.

The objectives of this study were to formulate and solve mathematical expressions for the application depths and rates from a self-propelled, center-pivot sprinkler irrigation system and to compare the theoretical distribution of application depths with actual field distribution measurements on two different installations. A Fortran II program was written for the 1620 IBM computer to evaluate the application depths and rates.

Paper No. 66-744 presented at the Winter Meeting of the American Society of Agricultural Engineers at Chicago, Ill., December 1966, on a program arranged by the Soil and Water Division. Approved for publication as paper No. 1141 in the journal series of the Colorado Agricultural Experiment Station. Contribution from Colorado Agricultural Experiment Station, Colorado State University and Colorado and Northern Plains Branch, SWCRD, ARS, USDA.

The authors—D. F. HEERMAN and P. R. HEIN—are junior agricultural engineer and graduate research assistant in agricultural engineering, Colorado State University, Fort Collins.

* Numbers in parentheses refer to the appended references.

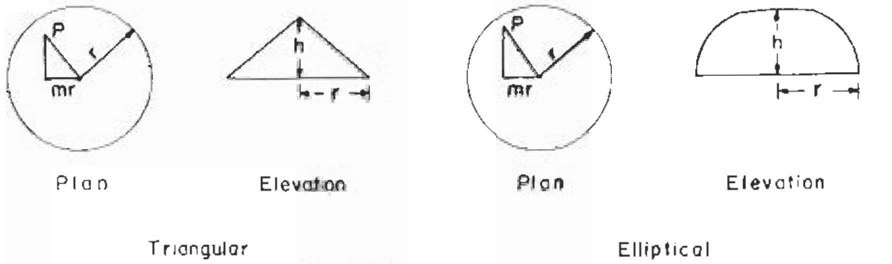


**FIG. 1** Application-rate patterns for stationary sprinkler.

## Description of System

The type of system studied consists of a line of sprinklers supported on wheels which rotate continuously about a center-pivot point. The line is approximately 1,300 ft in length and irrigates approximately 135 acres in one revolution. The two installations utilized for comparison of theoretical distribution with field measurements had approximate capacities of 600 and 950 gpm.

## Symbols and Dimensions

- p, a point on the field surface under investigation (dimensionless)
- $A$, rate of application on point p from one sprinkler $(L/T)$
- $h$, rate of application at center of sprinkler pattern $(L/T)$
- $r$, radius of sprinkler pattern (L)
- $D$, total depth of application on point p due to complete pass of a single sprinkler (L)
- $A_s$, rate of application from a sprinkler system at a distance, S, from the center of rotation $(L/T)$
- $D_s$, total depth of application from a sprinkler system at a distance, S, from the center of rotation (L)
- $T$, time required for one-half a single sprinkler pattern to pass point p (T)
- $\omega$, angular velocity of sprinkler lateral (radians/T)
- $S$, distance from center of rotation to point p (L)
- $R$, distance from center of rotation to sprinkler (L)
- $n$, ratio of radius of rotation to pattern radius, $R/r$ $(L/L)$
- $m$, ratio of distance from sprinkler to point p, measured along sprinkler line to pattern radius, $(S - R)/r$ (L/L)
- $\alpha$, angle of rotation about pivot (radians)
- $\phi$, angle of integration, equal to $\pi/2 - \alpha/2$ (radians)
- $i$, subscript referring to the $i^{th}$ sprinkler on the system (dimensionless)
- $C_u$, Christiansen's coefficient of uniformity (dimensionless)
- $V$, volume of application $(L^3)$
- $s$, subscript denoting a point at a distance S from center of rotation (dimensionless)

## Moving Single Sprinklers

This analysis requires mathematical expressions for application rate and depth from moving sprinkler heads. Bittinger and Longenbaugh (3) derived the mathematical equations for application rate and depth for single sprinklers moving in either a straight line or a circular path. They assumed individual sprinkler patterns having triangular and elliptical cross sections which represent generally the extremes for stationary distribution patterns.

### Application Rate

The application rate from one sprinkler moving in a circular path across point p for a triangular sprinkler pattern is:

$$A = h - \frac{h}{r}[S^2 + R^2 - 2RS\cos\alpha]^{1/2} \quad \ldots\ldots\ldots\ldots [1]$$

Similarly, the application rate from one sprinkler for an elliptical sprinkler pattern is:

$$A = \frac{h}{r}[r^2 - S^2 - R^2 + 2RS\cos\alpha]^{1/2} \quad \ldots\ldots\ldots\ldots [2]$$

The maximum application rate, $h$, for the triangular pattern is double the rate for the elliptical pattern for a stationary sprinkler with a given discharge and radius. However, the rate decreases much more rapidly for the triangular pattern as the distance from the sprin-

This article is reprinted from the Transactions of the ASAE (vol. 11, no. 1, pp. 11, 12, 13, 14 and 15, 1968), the Transactions of the American Society of Agricultural Engineers, Saint Joseph, Michigan

kler increases. Fig. 1 illustrates the stationary sprinkler pattern for the triangular and elliptical cross sections.

### Application Depth

The total depth of application from one sprinkler was evaluated by integrating the rate over the total time. The total depth from one sprinkler moving in a circular path assuming a triangular pattern is (See notation in Fig. 2):

$$D = 2hT - \frac{2h}{r\omega}\int_0^{\omega T}\left[S^2 + R^2 - 2RS\cos\alpha\right]^{1/2} d\alpha \quad \ldots\ldots [3]$$

Similarly, the application depth from a sprinkler moving in a circular pattern over point p with the elliptical pattern is:

$$D = \frac{4h}{\omega}(1 - m^2)^{1/2}\int_0^{\frac{\omega T}{2}}\left[1 - \frac{4n(n + m)}{1 - m^2}\sin^2\phi\right]^{1/2} d\phi \quad \ldots\ldots [4]$$

Bittinger and Longenbaugh were able to solve equation [3] in the form of an elliptic integral but did not solve equation [4].

They also indicated that the circular path could be approximated with a straight-line path beyond a distance from the pivot to the sprinkler of five times the pattern radius.

The equations for the application depth for the straight-line path for triangular and elliptical sprinkler patterns are, respectively,

$$D = \frac{hr}{\omega R}\left[(1 - m^2)^{1/2} - m^2 \ln\left|\frac{(1 - m^2)^{1/2} + 1}{m}\right|\right] \quad \ldots\ldots [5]$$

and

$$D = \frac{hr\pi(1 - m^2)}{2\omega R} \quad \ldots\ldots [6]$$

#### Overlapping Sprinkler Effect

Equations [3], [4], [5], and [6] can be utilized to evaluate the application depth for one sprinkler passing over any point. For this analysis both equations [3] and [4] are solved by a numerical method. The system analyzed in this paper, however, must consider the overlap from adjacent sprinklers to determine the total application at any particular point. The large number of repetitive solutions required to determine the distribution pattern for a system immediately requires the use of a computer.

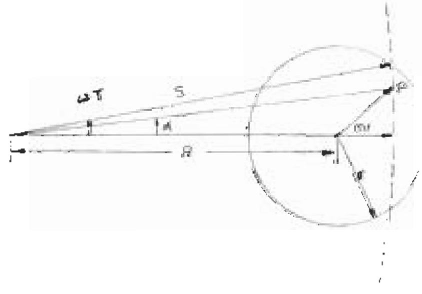


FIG. 2 Sprinkler moving in a circle at constant velocity.

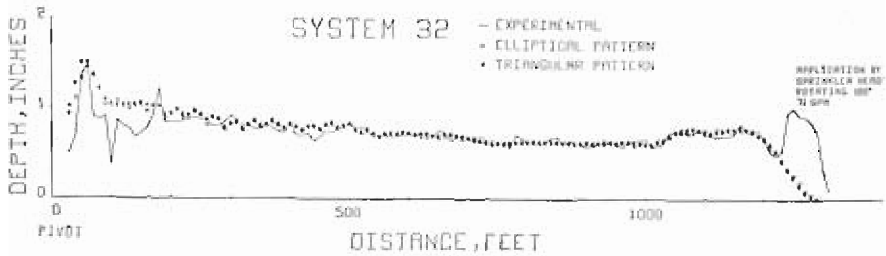


FIG. 3 Theoretical and measured application depth distribution for system 32.

The equations solved to determine the total depth at a distance S from the pivot for one pass of the system for the triangular and elliptical sprinkler patterns, respectively, are

$$D_s = 2\sum_{i=1}^{N} h_iT_i - \frac{h_i}{r_i\omega}\int_0^{\omega T_i}\left[S^2 + R_i^2 - 2R_iS\cos\alpha\right]^{1/2} d\alpha \quad \ldots\ldots [7]$$

and

$$D_s = \frac{4}{\omega}\sum_{i=1}^{N} h_i(1 - m_i)^{1/2}\int_0^{\frac{\omega T_i}{2}}\left[1 - \frac{4n_i(n_i + m_i)}{1 - m_i^2}\sin^2\phi\right]^{1/2} d\phi \quad \ldots\ldots [8]$$

The numerical solution of equations [7] and [8] require considerable computer time and therefore the application depth beyond 650 ft was approximated with equations [5] and [6] for the straight-line path. The amount of skewness for the circular path was less than 0.01 in. from the inner to the outer radius for one sprinkler at this distance. The equations solved for the total depth at a distance S from the pivot for one pass of the system with the straight-line approximation for the triangular and elliptical patterns, respectively, are

$$D_s = \sum_{i=1}^{N}\frac{h_ir_i}{\omega R_i}\left[(1 - m_i^2)^{1/2} - m_i^2 \ln\left|\frac{(1 - m_i^2)^{1/2} + 1}{m_i}\right|\right] \quad \ldots\ldots [9]$$

and

$$D_s = \frac{\pi}{2\omega}\sum_{i=1}^{N}\frac{h_ir_i}{R_i}(1 - m_i^2) \quad \ldots\ldots [10]$$

#### Comparison of Theoretical and Field Distribution

The adequacy of theoretical equations [7], [8], [9] and [10] for predicting the depth of application was determined by comparing with experimental measurements from an operational system. Field application depths were measured in cans spaced 10 ft apart and extending radially outward from the center-pivot point. The continuous lines in Figs. 3 and 4 are the measured application depths versus distance from the pivot point for two systems. The individual sprinkler pressures and angular velocity of the system were measured to allow a direct comparison of theoretical and field-measured depths.

The theoretical application depths were determined for 10-ft radial intervals for both triangular and elliptical patterns by solving equations [7], [8], [9] and [10] numerically on a computer. The individual sprinkler discharge and pattern radius were taken from the manufacturer's handbook corresponding to the sprinkler orifice size and pressure. Table 1 provides the sprinkler discharges, pattern radii, and radii of rotation used in the theoretical analysis of both systems. Plotted points in Fig. 3 and 4 represent theoretical depths for the triangular and elliptical patterns. The water discharged by the field installations utilized for comparison was greater than indicated in Table 1 by the amount necessary to propel the system plus the discharge for the large-volume sprinklers at the outer end of each system.

The system in Fig. 4 (No. 52) has a considerable reduction in application depth approximately 1,050 ft from the pivot. This dip results from sprinklers 31 and 32 inadvertently being much smaller than adjacent sprinklers and provides an excellent test of the theoretical distribution. The deviation between actual and computed depth 450 ft from the pivot results from a sprinkler head not revolving during the test. The application depth at the outer end of the line is due to a large volume gun rotating in a semicircle which was not included in the mathematical model.

Small differences are observed between the computed application depths for the triangular and elliptical sprinkler patterns. The close spacing of adjacent sprinklers probably conceals the effect of the different sprinkler patterns.

TABLE 2. COEFFICIENT OF UNIFORMITY

| System | Acres | Experimental | Theoretical Distribution | |
|---|---|---|---|---|
| | | | Triangular pattern | Elliptical pattern |
| 32 | 108.2 | 90.5 | 89.0 | 89.5 |
| 52 | 111.8 | 87.3 | 89.3 | 89.3 |

application rate for the triangular and elliptical patterns, respectively, are:

$$A_e = \sum_i h_i - \frac{h_i}{r_i}[S^2 + R_i^2 - 2R_iS \cos \alpha]^{1/2} \quad . . . . . . . . . [16]$$

and

$$A_t = \sum_i \frac{h_i}{r_i}[r_i^2 - S^2 - R_i^2 + 2R_iS \cos \alpha]^{1/2} \quad . . . . . [17]$$

Equations [16] and [17] were solved for small increments of $\alpha$ from zero to $\omega T$. This provided one-half of the symmetric rate-time relationship for a complete pass of the pattern over the point. With a given angular velocity, a rate vs. time relation was calculated for points at 100-ft intervals radially outward.

Each of the rate-vs.-time relationships were made dimensionless by dividing the rate by the maximum rate applied during the complete pass of the pattern and the time by the total time for a complete pass. Fig. 5 illustrates the dimensionless rate vs. time relationship for the triangular and elliptical patterns. For estimation purposes, the rate versus time curves were approximated with straight-line segments.

Sprinkler-irrigation design criteria specifies an allowable application rate. The total volume applied above the allowable (soil intake) rate can be considered potential runoff. The maximum application rate, which occurs directly under the sprinkler line, can be used to evaluate the portion of the total volume applied at a rate above some allowable rate. The excess percentage can be determined from the ratio of the allowable rate to the maximum rate occurring at various distances from the pivot. If a horizontal line were drawn on a time-rate plot at the fractional rate, the area above the line represents the portion of the total area under the rate-vs.-time curve for which the volume or depth being applied exceeds the allowable rate.

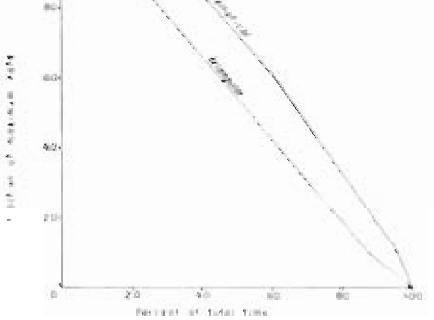

FIG. 5 Dimensionless application rate vs. time.

### Application Rate Analysis

The total volume applied above an allowable rate can be considered a depth per unit area. For purposes of illustration, the depth applied at an excessive rate was calculated assuming two allowable application rates of 0.3 and 0.5 in. per hr. The capacities of sprinklers 31 and 32 on system 52 were increased to correspond with adjacent sprinklers for this illustration. Figs. 6 and 7 show the percent of the total depth applied at a rate exceeding the allowable rates vs. distance from the pivot for the triangular and elliptical patterns, respectively. It is quite obvious that the system with the smaller capacity has less of the total volume applied in excess of an allowable rate. The excess depth is approximately the same for the smaller system with the lower allowable rate and the larger system with the higher allowable rate. The percent of the excess depth increases considerably as the distance increases from the pivot point, indicating that the length of line is a major factor in designing a center-pivot system.

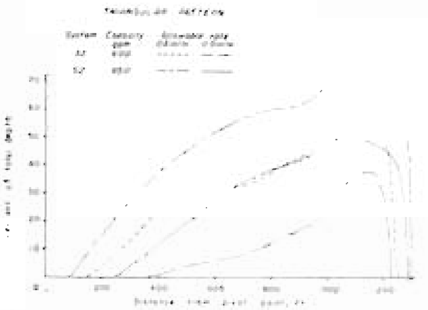

FIG. 6 Percent of total depth applied above allowable rate vs. distance from pivot for triangular pattern sprinklers.

The volumes applied at a rate in excess of the allowable rates are summarized in Table 3 which provides a better insight of the system performance. Again, the size of the system shows a marked effect on the volume applied at an excessive rate. When assuming an elliptical pattern and an allowable rate of 0.5 in. per hr, the excess volume for system 32 is less than 10 percent of the total. However, an increase in the size of system and a decrease in allowable rate to 0.3 in. per hr increases the excess volume to 50 percent of the total. With the triangular pattern assumption, the percent volume excess increases approximately 5 or 6 percent above that with the elliptical pattern. The percent excess represents the amount of irrigation water that could be potential runoff and could decrease the uniformity of application depth.

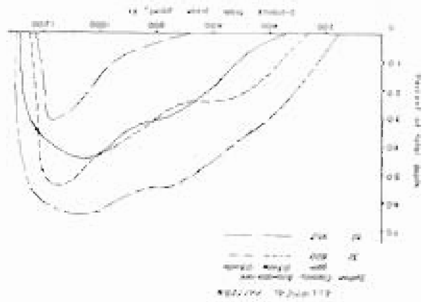

FIG. 7 Percent of total depth applied above allowable rate vs. distance from pivot for elliptical-pattern sprinklers.

The effect of the increased excess depth farther from the pivot point is magnified since the area irrigated increases as a function of the radius squared. As an illustration for a 1,300-ft circle, 50 percent of the area is outside of the 920-ft point and 75 percent of the area is outside of 650 ft. This again emphasizes the need to consider the length of line for design.

### Discussion

The analysis of the two systems indicates the problems for the design of a center-pivot sprinkler system for soils with low intake rates. The equations and figures presented can be used to determine the maximum allowable system length for a given set of conditions.

The total depth of application can be reduced by increasing the angular velocity and provide a proportionate decrease in the depth applied at an excessive rate. The percent of the total depth applied above an allowable rate remains constant as shown in Fig.

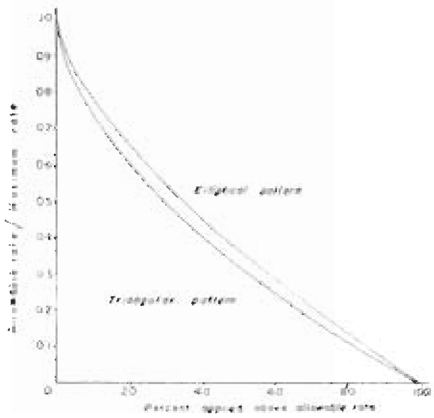


FIG. 8 Graphical solution for determining the percent of total value applied above an allowable rate.

## Uniformity of Depth

Figs. 3 and 4 both indicate a larger application depth near the center of rotation. A measure of uniformity would indicate the seriousness of this deviation. Uniformity evaluations of sprinkler-irrigation systems has been discussed by Beale and Howell (2). Comparisons were made of various coefficients to measure uniformity and relationships among the various coefficients. The "coefficient of uniformity" proposed by Christiansen (4) was considered to be a satisfactory measure of uniformity and was utilized in evaluating the uniformity in this analysis.

The uniformity coefficient considers the ratio of a summation of the absolute deviation of the mean volume from observed volumes for subareas to the total volume applied and can be expressed as

$$C_u = 100\left[1.0 - \frac{\sum_s \left|V_s - \bar{V}_s\right|}{V}\right] \quad \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots [11]$$

**Coefficient of Uniformity for Center-Pivot System**

The volume associated with the subareas, $V_s$, were assumed to equal the depth times the area represented by the point measurement. Each observed depth was assumed constant for one revolution of the system. By letting the distance between measured points be $\Delta S$, the area represented by depth at point $S$ is

$$A_s = 2\pi S_s \, \Delta S \quad \ldots \ldots \ldots [12]$$

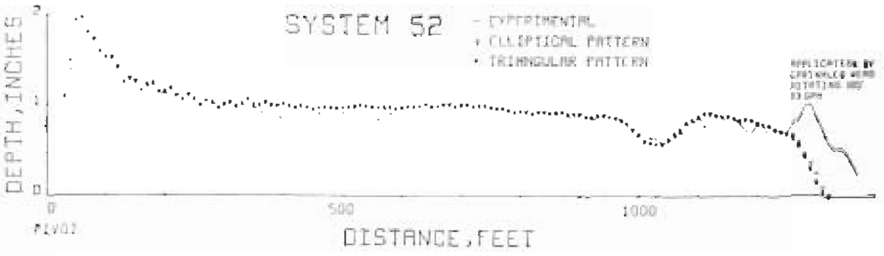


**FIG. 4** Theoretical and measured application depth distribution for system 52.

The volume for a subarea was expressed as

$$V_s = D_s A_s = 2\pi D_s S_s \Delta S \quad \ldots [13]$$

The average volume for a subarea is $\bar{V}_s = \bar{D}\, A_s$ where the average depth, $\bar{D}$, is the total volume divided by the total area, $\bar{D} = \sum_s V_s / \sum_s A_s$. Therefore, equation [11] is written as

$$C_u = 100\left[1.0 - \frac{\sum_s \left| 2\pi D_s S_s \Delta S - \frac{2\pi S_s \Delta S \sum_s 2\pi D_s S_s \Delta S}{\sum_s 2\pi S_s \Delta S}\right|}{\sum_s 2\pi D_s S_s \Delta S}\right] \quad \ldots \ldots [14]$$

or

$$C_u = 100\left[1.0 - \frac{\sum_s S_s \left| D_s - \frac{\sum_s D_s S_s}{\sum_s S_s}\right|}{\sum_s D_s S_s}\right] \quad \ldots \ldots \ldots \ldots \ldots \ldots [15]$$

Table 2 contains the coefficients of uniformity for both systems. The uniformity coefficients in this table were determined by excluding the area at the outer radius where the theoretical begins to depart from the experimental distribution due to the end gun. If this was not done for system 32, $C_u$ would be 80.9 and 81.7 for the triangular and elliptical patterns, respectively. Note that the deviation from the mean at the outer radius of the sprinkler system affects a significantly large area and reduces $C_u$ accordingly. Both systems appear to have excellent uniformity of application depth. The lower experimental $C_u$ for system 52 is probably the direct result of the malfunction of the 15th sprinkler located approximately 500 ft from the pivot.

Since Table 2 and Figs. 3 and 4 indicate good agreement between the theoretical and measured depths, it was assumed that the mathematical model could be used to determine the application rate at various points under the system.

TABLE 1. INVENTORY OF SPRINKLER SYSTEM

| Sprinkler number | System 32 r, ft | System 32 R, ft | System 32 Q, gpm | System 52 r, ft | System 52 R, ft | System 52 Q, gpm |
|---|---|---|---|---|---|---|
| 1 | 40 | 50.3 | 2.5 | 41 | 50.2 | 3.5 |
| 2 | 40 | 83.4 | 2.8 | 46 | 83.3 | 5.3 |
| 3 | 40 | 115.4 | 3.0 | 45 | 115.3 | 5.3 |
| 4 | 44 | 147.4 | 4.8 | 48 | 147.3 | 6.3 |
| 5 | 44 | 179.4 | 4.7 | 50 | 179.3 | 7.4 |
| 6 | 47 | 211.4 | 5.7 | 52 | 211.3 | 8.6 |
| 7 | 49 | 243.4 | 6.7 | 52 | 243.3 | 8.8 |
| 8 | 49 | 275.4 | 6.8 | 53 | 275.3 | 9.9 |
| 9 | 49 | 307.4 | 6.9 | 53 | 307.3 | 10.1 |
| 10 | 50 | 339.4 | 7.9 | 54 | 339.3 | 12.8 |
| 11 | 52 | 371.4 | 9.3 | 54 | 371.3 | 12.8 |
| 12 | 51 | 403.4 | 9.1 | 54 | 403.3 | 12.9 |
| 13 | 51 | 435.4 | 9.1 | 60 | 435.3 | 15.9 |
| 14 | 53 | 467.4 | 11.6 | 60 | 467.3 | 15.7 |
| 15 | 53 | 499.4 | 11.4 | 60 | 499.3 | 15.9 |
| 16 | 53 | 531.4 | 11.2 | 61 | 531.3 | 19.5 |
| 17 | 53 | 563.4 | 11.2 | 61 | 563.3 | 18.5 |
| 18 | 53 | 595.4 | 11.4 | 61 | 595.3 | 19.3 |
| 19 | 62 | 627.4 | 13.9 | 64 | 627.3 | 21.9 |
| 20 | 62 | 659.4 | 13.9 | 64 | 659.3 | 24.0 |
| 21 | 61 | 691.4 | 13.5 | 64 | 691.3 | 23.7 |
| 22 | 61 | 723.4 | 13.5 | 64 | 723.3 | 26.1 |
| 23 | 61 | 755.4 | 13.5 | 64 | 755.3 | 26.1 |
| 24 | 58 | 787.4 | 14.1 | 64 | 787.3 | 26.1 |
| 25 | 58 | 819.4 | 15.1 | 64 | 819.3 | 25.7 |
| 26 | 58 | 851.4 | 15.1 | 65 | 851.3 | 28.6 |
| 27 | 60 | 883.4 | 16.3 | 65 | 883.3 | 28.6 |
| 28 | 60 | 915.4 | 16.3 | 65 | 915.3 | 28.6 |
| 29 | 61 | 947.4 | 17.7 | 65 | 947.3 | 28.3 |
| 30 | 61 | 979.4 | 17.9 | 65 | 979.3 | 34.8 |
| 31 | 61 | 1011.5 | 17.7 | 60 | 1011.3 | 16.7 |
| 32 | 61 | 1044.6 | 17.9 | 59 | 1043.3 | 15.4 |
| 33 | 61 | 1068.6 | 20.2 | 66 | 1075.3 | 35.8 |
| 34 | 63 | 1092.8 | 20.8 | 66 | 1107.3 | 34.8 |
| 35 | 63 | 1125.7 | 20.8 | 70 | 1139.3 | 34.8 |
| 36 | 63 | 1149.7 | 20.8 | 75 | 1171.3 | 39.0 |
| 37 | 63 | 1173.6 | 23.1 | 75 | 1203.3 | 37.1 |
| 38 | 63 | 1206.7 | 23.1 | 74 | 1236.4 | 33.0 |
| 39 | 63 | 1230.7 | 14.3 | 63 | 1260.4 | 20.3 |
| 40 | | | | 42 | 1272.4 | 11.4 |
| | | | 495.6 | | | 809.3 |

## Application Rates

Near the pivot point, the application rate on a point is low but time of application is long. Moving radially outward the time of application on a point decreases with a corresponding increase in the application rate being necessary if uniform depth is to be achieved.

The application rate on a point at a distance $S$ from the pivot includes discharge from more than one sprinkler and can be determined by summing the individual rates from superimposed adjacent patterns. The equations for

TABLE 3. SUMMARY OF VOLUME APPLIED ABOVE ALLOWABLE RATES FOR ONE REVOLUTION OF THE SYSTEM

| System | Q gpm | Allowable rate | Hrs./Rev. | Total volume ac. — in. | Volume above allowable rate ac. — in. | Percent excess |
|---|---|---|---|---|---|---|
| | | | Triangular | | | |
| 32 | 600 | 0.3"/hr. | 73 | 80.6 | 30.5 | 37.8 |
| | | 0.5"/hr. | 73 | 80.6 | 12.8 | 15.9 |
| 52 | 950 | 0.3"/hr. | 60 | 113.9 | 62.8 | 55.1 |
| | | 0.5"/hr. | 60 | 113.9 | 39.5 | 34.7 |
| | | | Elliptical | | | |
| 32 | 600 | 0.3"/hr. | 73 | 80.1 | 25.3 | 31.6 |
| | | 0.5"/hr. | 73 | 80.1 | 7.8 | 9.7 |
| 52 | 950 | 0.3"/hr. | 60 | 113.2 | 57.0 | 50.4 |
| | | 0.5"/hr. | 60 | 113.2 | 31.8 | 28.1 |

5 and is not a function of the angular velocity.

A reduction of the system capacity decreases the percent of the total volume applied in excess of an allowable rate. The lower limit of a system is controlled by the amount necessary to meet the seasonal crop requirement. The two systems analyzed in this analysis, assuming 100 percent efficiency, provide 0.22 and 0.36 in. per day with continuous operation. With a system efficiency of less than 100 percent, the smaller system may have difficulty in maintaining optimum moisture conditions especially during growth periods with peak water demand.

## Design of System

The distribution of application depth under a center-pivot system can be estimated with assumed triangular and elliptical sprinkler patterns with equations [7], [8], [9] and [10]. The discharge in gallons per minute for individual sprinklers can be determined for a desired irrigation depth in inches and an angular velocity in radians per hr by

$$Q_i = \frac{D\omega R_i(R_{i+1} - R_{i-1})}{192} \quad [18]$$

The sprinkler spacing is dependent on the desired overlap and available sprinklers. The two systems used for comparison demonstrate the uniformity in depth of application that has been attained with the center-pivot sprinkler system as well as the nonuniformity in rate of application.

The analysis indicates that the application rate may be too high for many conditions. Two obvious solutions are to limit the length of the line or utilize sprinkler heads with a longer pattern radius. The longer pattern radius would provide a longer intake opportunity time and allow a reduction in application rate.

The design of a sprinkler lateral length can be made utilizing an allowable application rate corresponding to the soil intake characteristics. The maximum application rate at any point on the system can be determined with equations [16] and [17] at $\alpha = 0$. If the maximum application rate exceeds the allowable rate, the depth applied above this rate can be determined by finding the area above the appropriate rate ratio in Fig. 5. This integration is shown in Fig. 8 which allows a direct determination of the percent excess depth for a given sprinkler pattern, allowable rate, and maximum rate.

## Summary

1 Mathematical equations are given for the application depths and rates for a center-pivot sprinkler system. A method of evaluating the uniformity of application depth is presented.

2 Theoretical solutions for distribution of depth from a center-pivot sprinkler system are compared with field measurements.

3 The distribution of application rate radially outward from the center pivot is shown.

4 The analysis provides the formulation necessary for the proper design of a center-pivot, self-propelled, sprinkler irrigation system.

## References


1 ASAE Recommendation: Minimum requirements for the design, installation and performance of sprinkler irrigation equipment, American Society of Agricultural Engineers, approved February, 1953.

2 Beale, Jack G. and Howell, David T. Relationships among sprinkler uniformity measures. Journal of the Irrigation & Drainage Division, ASCE, Vol. 92, No. IR-1, Proceedings paper 4720, March 1966, pp. 41-48.

3 Bittinger, M. W. and Longenbaugh, R. A. Theoretical distribution of water from a moving irrigation sprinkler, Transactions of the ASAE, 5:(1)26-30, 1962.

4 Christiansen, J. E. Irrigation by sprinkling, bulletin 670, Agricultural Experiment Station, University of California, Berkeley, October, 1942.