Final Technical Completion Report of
OWRR Project A-040-Oklahoma
Agreement No. 14-31-0001-4036

IMPROVEMENT OF WATER APPLICATION OF SELF-PROPELLED SPRINKLER IRRIGATION SYSTEMS

Submitted to
The Office of Water Resources Research
Washington, D.C.

by
A. D. Barefoot
Assistant Professor of Agricultural Engineering
Oklahoma State University

Period Covered by Research Investigation
July 1, 1972 through June 30, 1975

The work upon which this report is based was supported in part by funds provided by the United States Department of the Interior, Office of Water Resources Research and Technology, as authorized under the Water Resources Research Act of 1964.

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INTRODUCTION

The number of center-pivot sprinkler irrigation systems is increasing in Oklahoma. The reasons for the increasing popularity are their labor-saving advantages and their versatility. The system's ability to irrigate rolling terrain with a wide range of application depths accounts for its versatility. The center-pivot system has proven to be very useful in applying light applications quickly to prevent wind erosion on soil. The light applications can also be beneficial in promoting seed germination. Greater depths of application can be applied when desired to meet water requirements of several different types of crops.

A recent survey conducted by Schwab (8) states that a total of 757,000 acres are under irrigation in Oklahoma. Approximately 312,600 of the 757,000 acres are irrigated by sprinkler systems. About 700 of the 3,231 sprinkler systems in Oklahoma are self-propelled. The survey lists 465 of these as being center-pivot systems. The initial cost of these center-pivot systems is in excess of eleven million dollars.

A USDA Inter-Agency Committee was appointed in 1970 to study the suitability of center-pivot sprinkler irrigation systems under Oklahoma conditions. Three factors were responsible for the study: (1) increasing farmer interest in such systems, (2) the difficulties some farmers have experienced with these systems, and (3) the need for developing uniform guidelines for agency use when advising farmers.

Some excerpts from the engineering guidelines of the committee report are:

The irrigation system should have the capacity to meet the peak moisture demands of all crops that the purchaser may desire to irrigate within the design area.

The application rate for the particular length of sprinkler line to be used should not cause runoff during the water application period.

The total depth of application (equivalent rainfall) per irrigation should be governed by the moisture storage capacity of the soil and the principle root zone depth of the crop irrigated.

Uniformity of water application on the field in total is affected by the sprinkler discharge rate, sprinkler spacing, and the constancy of speed of travel over the ground.

Successful operation of self-propelled irrigation systems is dependent upon maintaining traction on wetted soils.

Two inches of water applied every 6 days will result in approximately 20 percent less evaporation losses than using two-1-inch applications 3 days apart.

Because of the design procedures and intended use of center-pivot systems, it is sometimes not possible to meet the recommended guidelines for the systems. Center-pivot systems have high rates of application and can cause undesired runoff on soils with low infiltration capacities. Infiltration rates are not used as a basis for the design of center-pivot systems. Center-pivot systems sometimes have difficulty applying enough water to meet certain crop demands. Trafficability of these systems also can be a problem on certain soil types. It is because of such factors that research is needed to evaluate the effectiveness of water application from center-pivot systems.

Original Objectives

1. To evaluate the depth, rate, and uniformity of application of self-propelled sprinkler irrigation systems.
2. To determine the depth of water stored in the crop root zone of the soil.
3. To determine the evaporation losses for recommended light applications with high pressure nozzles under Oklahoma's windy conditions.
4. To evaluate the trafficability of these systems for several soil types.
5. To determine crop yields per acre and yield per acre-inch of water applied.

Review of Literature

Christiansen's coefficient of uniformity is generally used as a basis for describing uniformities of application in sprinkler irrigation (7). The formula used in calculating the coefficient is:

$$Cu = 100\ (1.0 - \frac{\Sigma x}{MN})$$

where: Cu = Uniformity coefficient, percent
x = Deviation of individual observations
M = Mean value
N = Number of observations

Pair (6), Sternberg (9), and Davis (2) used catch cans to collect spray samples from operating sprinkler systems. The catch cans were made of quart oil cans and were placed in a grid system. The most commonly used grid spacing was 5 feet. The volume collected in the cans was measured with graduated cylinders. Kerosene was placed in the cans to supress evaporation during sampling.

Heermann and Hein (4) compared theoretical distributions from center-pivot systems with actual field distributions. The center-pivot system used was 1,300 feet in length and irrigated approximately 135 acres in one revolution. Experimental uniformities were reported as being 90.5 and 87.3 for flow rates of 950 and 600 gallons per minute, respectively. These values were compared to theoretical distributions for triangular patterns and elliptical patterns. The coefficients of uniformity were 89.0 and 89.3 for the triangular pattern and 89.5 and 89.3 for the elliptical pattern, respectively for the 950 and 600 gallons per minute flow rates.

Pair (7) found uniformity coefficients from a center-pivot system of 81 for a 7.1 miles per hour wind and 86 for a 5.0 miles per hour wind. The system tested traveled at a rate of 1 revolution in 48 hours.

Probably the most researched subject about sprinkler irrigation is that of application losses. This involves losses due to drift, evaporation and evapotranspiration.

In an extensive study of sprinkler irrigation, Christiansen (1) investigated spray evaporation losses. The catch can method was employed and values of loss ranged from 10 to 42 percent. No correlations of losses with climatic variables was observed.

Frost and Schwalen (3) investigated combined spray evaporation and drift losses, also by the catch can method. They obtained good correlation between spray losses and vapor pressure deficit. They also found that losses were approximately proportional to nozzle pressure and wind speed and inversely proportional to nozzle diameter.

In research conducted by Kraus (5), it was found that total application losses from sprinkler systems ranged from 3.4 to 17 percent. A direct relationship between loss and humidity was established. No accurate correlation was made with wind because of its difficulty to measure. Kraus also reported that 36 percent of the total loss was due to drift.

Frost and Schwalen (3) also investigated evapotranspiration loss in sprinkler irrigations. It was found that evapotranspiration losses during sprinkling may be neglected when calculating application losses. This is because they are about equal to normal evapotranspiration losses when not sprinkling. Evapotranspiration losses reached a peak near midday and also increased with vapor pressure deficit and wind velocity.

Evapotranspiration from irrigated peanuts has been studied at the Caddo Peanut Research Station at Fort Cobb, Oklahoma (10). The values for evapotranspiration obtained from these studies are listed in Tables I and II.

TABLE I

Evapotranspiration for 1969, Based on Neutron Probe Determination

	Total ET For Period (In. Water)			
	North-South Oriented Rows		East-West Oriented Rows	
Date	**12"	36"	12"	36"
August 11-20	0.48	1.22	0.81	1.36
August 22-30	0.38	0.85	0.75	0.72
September 4-10	1.04	1.86	1.25	1.18

TABLE II

Evapotranspiration for 1971, Based on Neutron Probe Determination

	Total ET For Period (In. Water)			
	North-South Oriented Rows		East-West Oriented Rows	
Date	**12"	36"	12"	36"
August 2-12	0.56	0.67*	0.82	-
August 16-21	0.85	1.47*	1.04	1.39

* Value from 1 tube
** Row spacing

EXPERIMENTAL EQUIPMENT

The data collected for this research project was collected from the Zimmatic, Model 310, self-propelled center-pivot sprinkler irrigation system shown in Figures 1 and 2. The system was a standard ten tower unit with an overall length of 1,200 feet. The system was electrically driven. Each tower contained a 1 horsepower drive motor. The motors were supplied with a direct drive to the wheels eliminating any slippage in the drive mechanism.

The time of rotation for the system could vary from 20 hours to 200 hours. This rotation time was controlled by a speed setting control based on a percentage of time. This means that the system was only moving a certain percentage of the time. For example, if the speed setting was 50 percent, the system would be moving 50 percent of the time. The 20-hour rotation time required a setting of 98 percent, while the 200 hour required 10 percent. The 40 percent setting was used most often while data were collected. As the speed setting is increased, the depth of application is decreased.

Center-pivot systems vary a great deal in sprinkler design. Some pivot systems have only one size of sprinkler head and vary the spacing of the sprinkler heads to obtain desired application rates. Other sprinkler systems use constant spacings and vary the size of the sprinkler heads. On the Zimmatic system, both the spacings and the size of the heads are varied to obtain desired application rates. The Zimmatic system was designed to deliver 800 gallons per minute at a pivot pressure of 77 pounds per square inch. Manufacturer's data also suggests that the system will deliver 774 gallons per minute at a pivot pressure of 72 pounds per square inch. Pressures lower than this are not recommended as a satisfactory operating pressure.

The sprinkler system was used to irrigate the center 125 acres of a quarter section of land. Peanuts were grown on the north half of this 125 acres and milo was grown on the south half. All data were collected while irrigating peanuts. The peanuts were planted in rows with spacings of 33-11-16-11. These numbers are the distance between adjacent rows in inches. The rows were planted in the east-west direction.

The catch can method was used to collect sprinkler spray samples. The catch cans, number 3 squat cans obtained from a food canning plant, were 3-7/16 inches in height and 4-1/8 inches in diameter with a sharp edge and no lids.

The inflow into the irrigation system was measured with an 8-inch flow meter. The flow meter was calibrated in the Agricultural Engineering Laboratory at Oklahoma

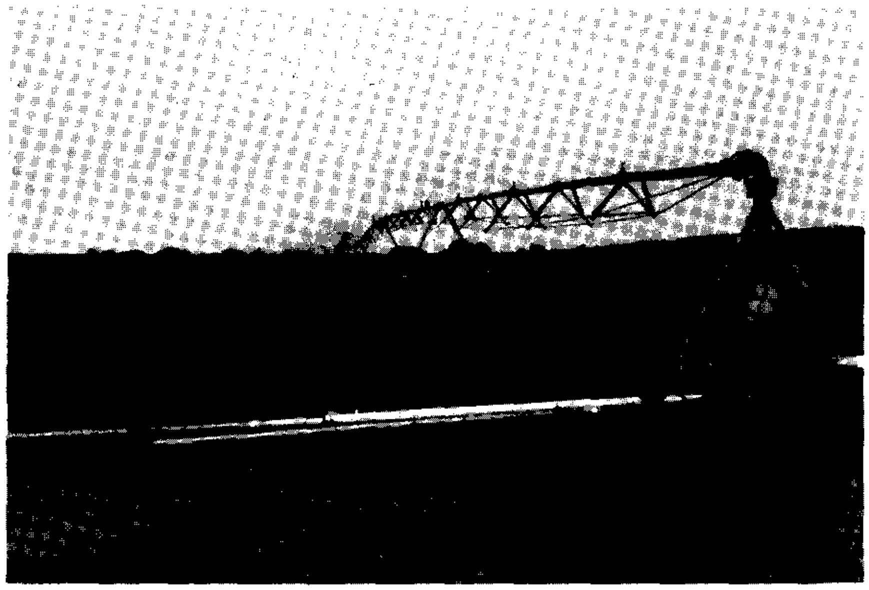

Figure 1. Zimmatic Self-Propelled Center Pivot System.

Figure 2. Last Tower of Pivot System.

State University using a 6-inch flow meter that had been calibrated with a sharp-edge orifice and a U-tube manometer at the Outdoor Hydraulic Laboratory near Stillwater, Oklahoma. The meter was installed in a 20-foot length of 8-inch aluminum irrigation pipe.

The wind speed was measured with a cup type anemometer and the direction with a wind vane. A recording type rain gage was used to measure precipitation.

Soil moisture measurements were taken by both the gravimetric or oven-dry method and the neutron probe. The gravimetric sampling device was made of cadmium plated steel and was approximately 36 inches in length. The soil samples were kept in tin sampling cans and were dried in a portable bench-type oven. The neutron probe used was a Nuclear-Chicago Model P-19.

Pressure measurements were taken at the pivot by means of a standard pressure gage, with a range of 0 to 100 pounds per square inch. Pressures along the system were measured by a pitot tube and pressure gage combination.

Procedure

Catch cans were placed in single lines which extended radially from the pivot. The direction of these lines from the pivot were northeast, north, north-northwest, and west. A contour of the land was established in each of these directions. The cans were spaced at 20-foot intervals in the field prior to an irrigation. The volume of water caught in each can was measured with a graduated cylinder and recorded. Flow, wind and pressure measurements were also taken during each irrigation.

Gravimetric soil samples were taken throughout the irrigation season. These samples were taken to a depth of 24 inches in the soil profile. Four samples were obtained from the 24-inch profile. They were 0-6 inch, 6-12 inch, 12-18 inch, and 18-24 inch. The soil moisture samples were kept in air tight tin sample cans until they were weighed before drying. The samples were dried in a bench oven at 105°C for approximately 12 hours and then weighed again.

The soil samples were taken along the west and northeast test lines. Four sample locations were chosen along each line at approximately 300-foot increments from the pivot. At each test location, three samples of the soil were taken. This gave three samples for each of the 4 depths in profile at each of the 4 locations in the individual lines. The three samples were put in the same sample can. This allowed an average soil moisture to be determined for each depth.

Neutron probe soil moisture measurements were also taken extensively during the irrigation season. Access tubes for the probe were installed at eight locations in the field along the northeast and west test lines. Four tubes were installed on each line at 300-foot increments from the pivot.

Probe readings were taken to a 45-inch depth in the soil profile. The probe was positioned in the profile at depths of 6, 12, 18, 24, 30, 36, and 42 inches. The 6-inch position sampled the 0-9 inch zone while the remainder of the sample positions had a sampling zone of 6 inches.

Sample plots in the field were harvested to determine the yield per acre of the peanut crop. Eight plots were harvested at each of the eight soil moisture testing locations. The plots consisted of two rows, eleven inches apart and ten feet in length. The plots were harvested by hand and were left on the vine to air dry to about 10 percent moisture content. The peanuts were then removed from the vine and were hand shelled. The moisture content of the shelled peanuts was determined with an electronic tester. A calibration curve for the electronic tester was used to convert the moisture to an oven-dry basis. The peanuts were then weighed to determine the total weight for each sample location.

Analysis of Data and Presentation of Results

The volume of water from each catch can was obtained by pouring it into a two-inch diameter graduated cylinder. The depth of application was calculated by dividing the volume by the cross-sectional area of the can. These depths were then analyzed for uniformity using Christiansen's uniformity coefficient as expressed by:

$$Cu = 100\ (1.0 - \frac{\Sigma x}{MN})$$

where: Cu = Uniformity coefficient, percent
x = Deviation of individual observations
M = Mean value
N = Number of observations

Data for wind speed and direction were collected during each irrigation. The wind speed was taken to be the average over the entire irrigation. The uniformity coefficient and wind speed of each irrigation is given in Table III.

The uniformity of the system was found to decrease slightly with wind speed as shown in Figure 3. The relationship between the coefficient of uniformity and wind speed appears linear. The overall uniformity of the system was found to be very good with all coefficients above 80%. A coefficient of 100% indicates perfect uniformity.

TABLE III. SYSTEM UNIFORMITY OF APPLICATION

LOCATION	DATE	DEPTH OF APPLICATION (INCHES)	UNIFORMITY COEFFICIENT (%)	SPEED SETTING (%)	AVERAGE WIND SPEED (MPH)	DIRECTION OF WIND	PRESSURE AT PIVOT (PSI)
West	8-07	0.56	83.7	35	4.8	SSE	60
NE	8-14	0.26	84.0	95	5.2	SE	70
NORTH	8-14	0.26	85.6	95	5.2	SE	69
NNW	8-14	0.27	90.4	95	5.2	S	69
NORTH	8-16	0.60	87.3	40	5.8	SSE	72
NE	8-20	0.57	86.1	40	5.8	ESE	73
NORTH	8-21	0.69	85.1	40	2.8	S	75
NNW	8-21	0.52	81.5	40	6.9	SE	69
NNW	8-24	0.54	85.5	40	11.8	SSW	62
NORTH	8-24	0.60	81.8	40	13.9	S	64
NE	8-25	0.56	85.9	40	9.0	S	65

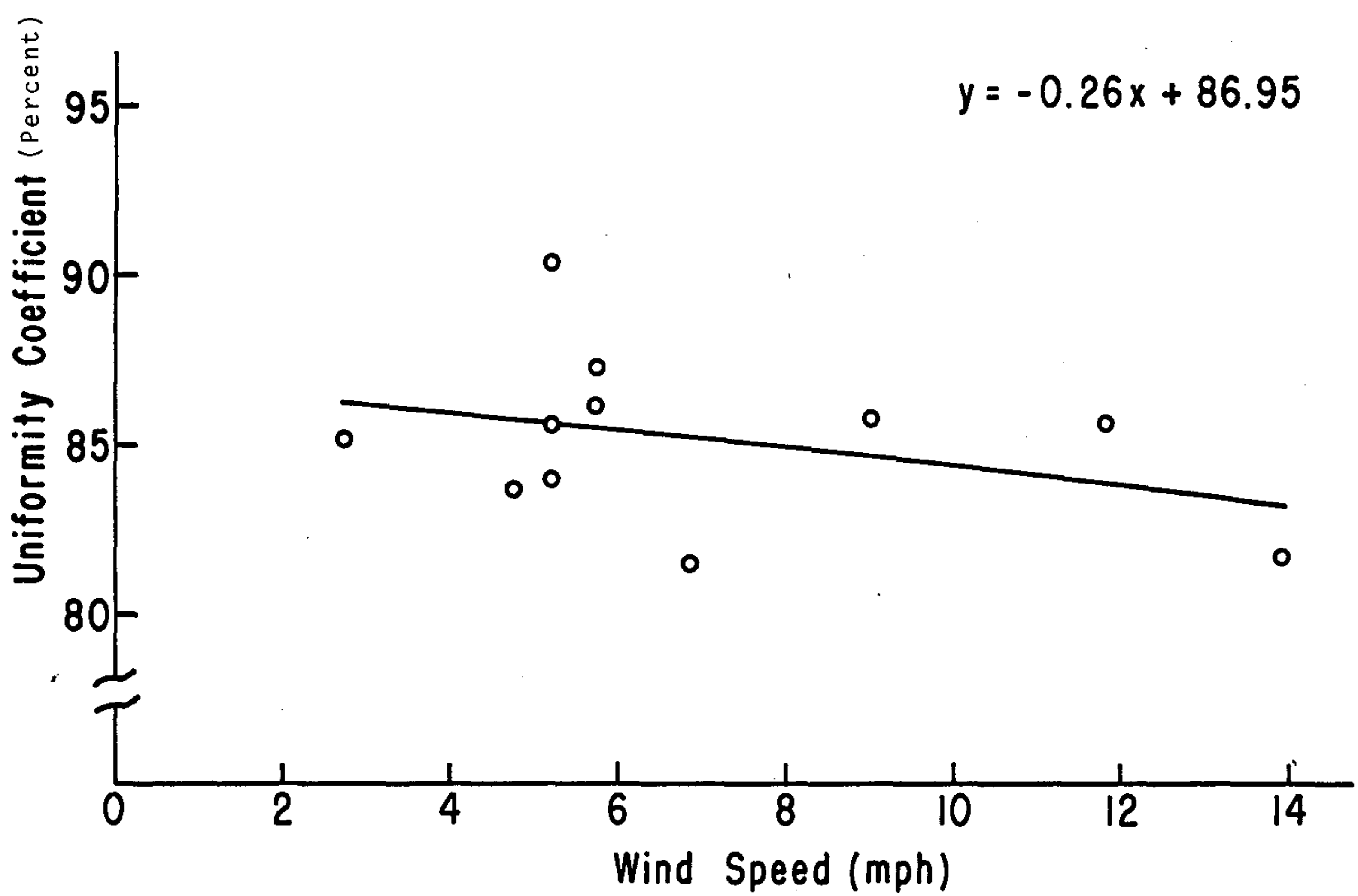

Figure 3. Coefficient of Uniformity Versus Wind Speed.

The soil moisture data from both the gravimetric and neutron probe methods were used to determine values of evapotranspiration. Evapotranspiration as used here is the sum total of evaporation and transpiration of the water after it has come in contact with the ground and vegetation surfaces. This does not include losses between the system and the ground. The average evapotranspiration values given by this analysis are listed in Tables IV and V. These values compared well with those reported by Stone (10).

The evaporation loss considered in this research occurred between the sprinkler nozzle and the ground surface. The difference between the depth of water caught in the catch cans and the amount of water leaving the system was considered to be the evaporation loss. Some of this loss was in the form of drift instead of actual evaporation. The drift element was not considered independent of evaporation.

The amount of water leaving the system is by continuity equal to the amount entering the system. This quantity of water was measured with the flow meter.

The percent difference in the calculated depth and that caught in the catch cans was the percent evaporation loss.

The evaporation loss ranged from zero to 30.9 percent with an average of 15.5 percent. The average night evaporation was 10.6 percent and the average day evaporation was 20.4 percent.

The weight of the peanut samples was obtained for each plot harvested to determine crop yields. The weight was recorded at 10 percent moisture content. The effective area of the plot was reported in acres. The sample plot consisted of two rows, eleven inches apart and ten feet in length. The total row spacing of the crop was 33-11-16-11. One-half of the skip distance between rows was taken on each side of the eleven-inch skip to be effective width. Thus, the effective width was 16.5 plus 11 plus 8 or 35.5 inches. The total area of the rectangular plot was calculated to be 0.000679 acres. The crop yields are reported in tons per acre in Table VI.

The total amount of water applied to each test location was recorded for the season. This enabled the yields per acre-inch of water applied to be determined. These results are also tabulated in Table VI.

From the results of yield per acre-inch of water applied, the values for the west test locations were 15.02 percent less than those for the northeast test locations. This can be explained by comparing the values of evapotranspiration for both lines. The values of evapotranspiration observed for both lines should be for the same time period. The values calculated using

TABLE IV. EVAPOTRANSPIRATION VALUES OBTAINED FROM ANALYSIS OF OVEN DRY SOIL MOISTURE DATA

LOCATION	DEPTH IN SOIL	JUL 20-OCT 18 (IN/DAY)	JUL 20-AUG 25 (IN/DAY)
W	21	0.181	0.174
W	15	0.170	0.163
W	12	0.172	0.160
		JUL 11-OCT 18 (IN/DAY)	JUL 11-AUG 25 (IN/DAY)
*NE	21	0.168	0.166
*NE	15	0.177	0.165
*NE	12	0.175	0.156

*VALUES OBTAINED WERE FROM LOCATION NE-1 AND NE-2 ONLY

TABLE V. EVAPOTRANSPIRATION VALUES OBTAINED FROM ANALYSIS OF NEUTRON PROBE SOIL MOISTURE DATA

LOCATION	DEPTH IN SOIL	JUL 10-OCT 18 (IN/DAY)	JUL 10-AUG 25 (IN/DAY)
*W	45	0.212	0.225
NE	45	0.189	0.205
W	21	0.186	0.209
NE	21	0.169	0.160
W	15	0.190	0.196
NE	15	0.177	0.166
W	12	0.189	0.195
NE	12	0.178	0.154

*VALUES OBTAINED WERE FROM LOCATION W-1,W-2 AND W-4 ONLY the neutron probe soil moisture data were calculated for the same time period. The values show a significant difference between the two lines. The west line indicates 21.27 percent more evapotranspiration than the northeast line. In effect, the northeast line had more water available for crop production.

SYSTEM COMPARISONS

Over one-half of the center-pivot sprinkler systems in Oklahoma are in four northwest counties. Many of these are on clay loam soils where more traction and runoff problems would be expected to occur. In the summer of 1974 data were collected from five systems in the Oklahoma Panhandle. Results of the analysis of this data are in Table VII.

Summary

The Zimmatic center-pivot sprinkler irrigation system was very effective in applying light applications. The average uniformity coefficient of the system was 85.2 percent with a standard deviation of 2.48. The uniformity appeared to decrease linearly with wind speed for the range of wind speeds tested. This relationship may not hold true for higher wind speeds than those tested. The largest percent difference between the observed data and the linear correlation was 5.55.

The uniformities of application compared very well with those found in previous investigations. Pair (7) found the uniformity of a center-pivot system to be 81 percent for a 7.1 miles per hour wind and 86 percent for a 5.0 miles per hour wind. The values obtained from this research were 85.1 percent for a 7.1 mile per hour wind and 85.7 percent for a 5.0 mile per hour wind. Heermann and Hein (4) found a coefficient of 87.3 percent for a flow rate of 600 gallons per minute. This compared very well with the average value of 85.2 percent found in this research.

The depths of application from the center-pivot system were typically light. The light applications were applied in a relatively short period of time. For crops that require light, frequent irrigations, such as peanuts, the center-pivot system proved to be ideal. The light applications also proved to be a tremendous asset in the prevention of wind erosion. The light applications may also be desirable for seed germination.

The evapotranspiration of the peanuts under the center-pivot system was found to be similar to that found under other types of sprinkler irrigation systems. Stone (10) reported evapotranspiration values for peanuts in western Oklahoma. These values were shown to be dependent upon both row spacing and the direction of orientation of the rows. Because of the varying row spacing in the field

TABLE VI. CROPS YIELDS PER ACRE-INCH OF WATER APPLIED

LOCATION	% MOISTURE (STEINLITE)	% MOISTURE (OVEN-DRY)	WEIGHT (GRAMS)	WEIGHT IN GRAMS AT 10% MOISTURE (OVEN-DRY)	YIELD IN TONS/ACRE AT 10% MOISTURE (OVEN-DRY)	AVERAGE YIELD IN (TONS/ACRE)	TOTAL WATER APPLIED (INCHES)	YIELD/ACRE-INCH OF WATER APPLIED (TONS/ACRE-INCH)
NE-1	12.47	13.10	1439.50	1400.05	2.27			0.116
NE-2	10.73	11.06	1236.90	1225.09	1.99			0.101
NE-3	10.50	10.80	1245.20	1236.32	2.00			0.102
NE-4	14.86	15.90	1472.60	1397.54	2.27	2.13	19.65	0.116
W-1	8.28	8.20	1084.00	1102.45	1.79			0.091
W-2	7.34	7.10	1168.00	1199.63	1.94			0.098
W-3	10.42	10.65	1163.50	1156.66	1.88			0.095
W-4	10.38	10.64	1018.20	1012.67	1.64	1.81	19.72	0.083

TABLE VII. COMPARISON OF FIVE SYSTEMS

NUMBER OF TOWERS	AREA IRRIGATED (ACRES)	DRIVE	SPRINKLER SIZE	SPRINKLER SPACING	DEPTH OF APPLICATION (INCHES)	AVERAGE WIND SPEED (MPH)	PRESSURE (PSI)	UNIFORMITY COEFFICIENT (%)
10	175	electric	fixed	variable	0.92	4.4	46.5	91.6
12	112.7	water	variable	variable	0.74	11.1	75.0	83.0
7	70.8	electric	variable	fixed	0.52	12.1	80.0	87.9
10	144.2	electric	variable	fixed	0.67	15.1	70.0	72.7
16	203.8	water	variable	fixed	1.36	6.1	105.0	73.1

tested, it was not possible to directly compare the results of this research to Stone's (10). However, the values reported in this research are in the same general range as those reported by Stone (10).

The evaporation loss from the system compared very well with those reported in previous research. Christiansen (1) found evaporation losses of 10 to 42 percent. The losses found in this study ranged from zero to 30.9 percent. The average loss during night irrigation was 9.8 percent less than the average loss for daytime irrigation.

Results from the systems tested in the Oklahoma Panhandle indicate a better uniformity coefficient for the shorter systems. Pressure did not have as much effect on uniformity as was expected.

No traffic problems were observed with the Zimmatic in the sandy soil. Only minor problems were observed in the clay loam soils in the panhandle; however, depth of applications were very light. They ranged from 0.52 inches to 1.36 inches. Heavier applications would cause greater traction problems.

Conculsions

1. The average coefficient of uniformity of the Zimmatic center-pivot system was 85.2 percent with a standard deviation of 2.48.

2. The uniformity of application of the center-pivot system decreased linearly with wind speed for the range of wind speeds tested.

3. Crop yields were 0.109 ton per acre-inch of water applied for the northeast test line and 0.092 for the west line.

4. Crop yields were inversely related to evapotranspiration.

5. The average value of evapotranspiration for the entire growing season of peanuts in Caddo county, Oklahoma was 0.186 inches per day.

6. The average evaporative loss from the system was 15.5 percent. The average loss during daytime irrigations was 20.4 percent and the average at night was 10.6 percent.

7. Trafficability of the center-pivot system was extremely good on sandy soil. Trafficability was a problem on the clay loam soils for large depths of application.

8. The average uniformity coefficient for the five systems tested in the Oklahoma Panhandle was 81.7 percent.

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