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Center Pivot Design Capacities in Eastern Colorado

By Dale F. Heermann,[1] Hollis H. Shull,[2] and Rome H. Mickelson[3]

Introduction

Center pivot sprinkler irrigation systems are being used extensively on newly developed irrigated areas. A 1972 survey (6) has shown that 1,040,590 acres in Colorado, Kansas, and Nebraska are being irrigated with center pivot sprinkler irrigation systems. System capacities in the Central Great Plains range from 4.5 gpm/acre-8 gpm/acre (6 mm/day-11 mm/day) with the most prevalent size being 6.5 gpm/acre (9 mm/day).

The system capacity is designed for peak evapotranspiration and modified by experience in using these systems in the area. Center pivot systems enable more frequent irrigations and smaller application depths than are feasible with most surface systems. The maximum application depth with center pivot systems is generally limited by intake capacity.

The objective of this study was to develop design system capacities by simulation of center pivot irrigation in eastern Colorado on soils with different available water holding capacities.

Procedure

Simulation Model.—Stegman and Shah (13) and Lembke and Jones (8) have demonstrated that a simulation model is a useful tool for evaluating irrigation systems. A model allows evaluation of a much longer climatic period than is normally feasible with direct field observations. The USDA irrigation scheduling program (7) has been adapted for simulating irrigation with center pivot systems.

The scheduling program uses the modified Penman equation for calculating

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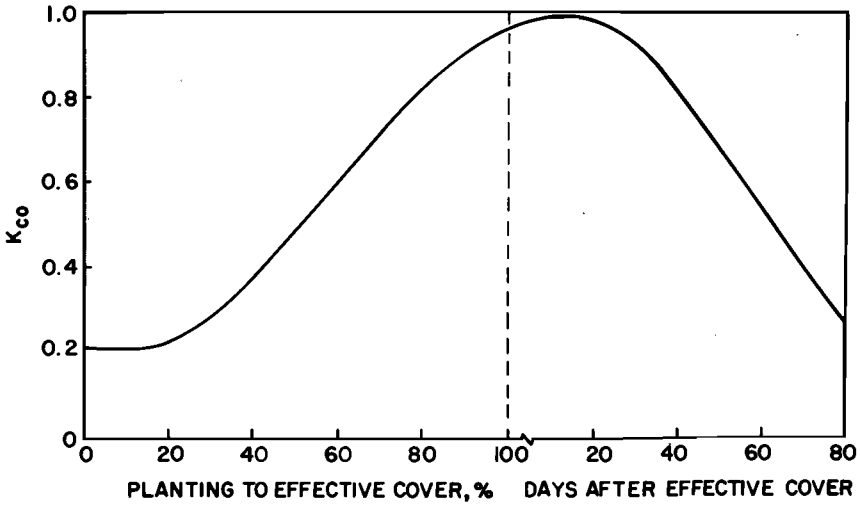

FIG. 1.—Crop Coefficient for Corn

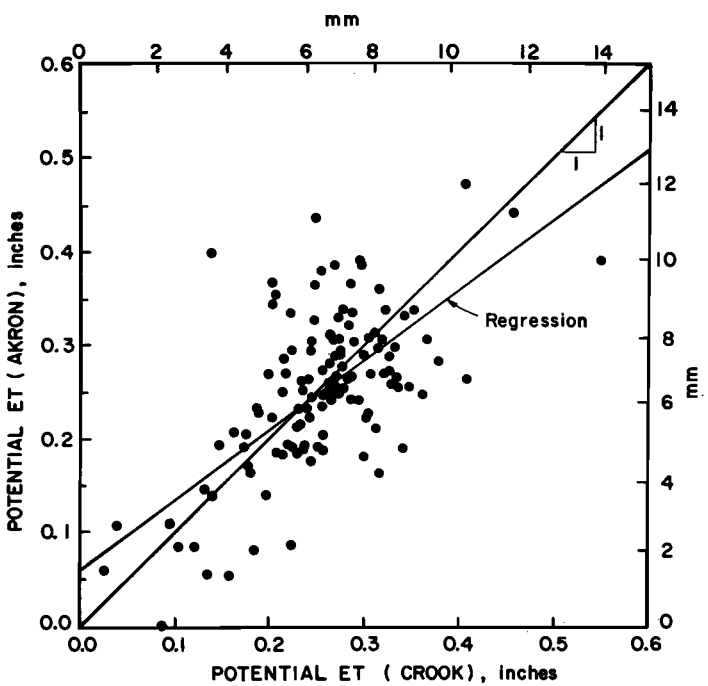

FIG. 2.—Comparison of Penman Potential ET with Adjusted Wind and Vapor Pressure for Akron and Crook (1971)

potential evapotranspiration (ET). The program has been successfully used for scheduling a surface irrigation system at the University of Nebraska Experiment Farm, Mitchell, Neb., and center pivot irrigation systems near Crook and Yuma, Colo. A water budget of the available soil water is maintained in the program and is formulated by

$$\mathrm{AW}(n) = \sum_{i=1}^{n} [R_e(i) + I(i) - \mathrm{ET}_a(i) - W_d(i)] + \mathrm{AW}(o) \quad (1)$$

in which AW(n) = the available water in the nth period; ET_a = actual evapotranspiration in the ith period; R_e = effective rainfall in the ith period; I = irrigation water applied in the ith period; and W_d = drainage from the root zone in the ith period.

Effective rainfall is assumed to equal the total rainfall occurring less surface runoff. However, any effective rainfall which exceeds the available water holding capacity is assumed lost to drainage from the root zone, W_d, and increased evaporation following rainfall is taken into account.

The evapotranspiration for corn is calculated by

$$\mathrm{ET}_a = K_c \mathrm{ET}_o \quad (2)$$

in which ET_o = potential evapotranspiration for a reference crop; and K_c = a dimensionless coefficient. The potential evapotranspiration is calculated by the modified Penman equation examined later. The coefficient, K_c, combines the effects of the resistance of water movement through the soil to the various evaporation surfaces, the resistance to the diffusion of water vapor from plant and soil surfaces to the atmosphere, and the relative amount of radiant energy available to the plant compared to that available to the reference crop (7). The crop coefficient is adjusted for soil surface wetness and soil water availability as follows:

$$K_c = K_{co} K_a + K_s \quad (3)$$

in which K_{co} = a mean crop coefficient (ratio of crop ET to ET_o, Fig. 1) based on experimental data where soil water is not limiting and normal irrigation plant populations are used; and K_a = a soil water coefficient that adjusts K_c for where there is some depletion of soil water.

It is equal to the logarithm of the percentage of the remaining available soil water, AW:

$$K_a = \frac{\log(\mathrm{AW} + 1)}{\log(101)} \quad (4)$$

in which K_s = a coefficient which accounts for the increase in ET due to a wet soil surface following an irrigation or rainfall. The value of K_s is approximated for the first, second, and third day after rain or irrigation, respectively, by: $(0.9 - K_{co}K_a)0.8$; $(0.9 - K_{co}K_a)0.5$; and $(0.9 - K_{co}K_a)0.3$. The value of $K_s = 0$ for days when $K_{co}K_a \geq 0.9$.

The rooting depth or zone from which water is available to the corn is assumed to be 1.5 ft (0.5 m) at the planting date (May 1) and increases to 4 ft (1.2 m) at full maturity (September 30). The rooting depth is assumed to increase linearly from 1.5 ft-4.0 ft (0.5 m-1.2 m) between June 20 and July 20 and then remains

constant. The rooting depth extension was developed from examination of water use studies of corn by Howe and Rhoades (5).

Calibration of Model.—The modified Penman equation was calibrated for the Central Great Plains with alfalfa as the reference crop. The potential ET as used herein is defined as the water used from a well watered reference crop like alfalfa with 12 in.-18 in. (300 mm-460 mm) of top growth. The potential ET for alfalfa was measured during the 1969, 1970, and 1971 seasons at the University of Nebraska Experiment Station, Mitchell, Neb. Two beam-balance weighing lysimeters with a strain gage readout similar to the type used by van Bavel and Myers (10) continuously recorded water use by the alfalfa crop. These lysimeters are sensitive to weight changes equivalent to 0.002 in. (0.05 mm) of water. The 3-acre field of alfalfa was irrigated with a center pivot irrigation system. An irrigated area extends approx 10 miles (16 km) upwind towards the direction of prevailing winds.

Solar radiation, net radiation, air temperature, precipitation, wind speed, and dew point temperature were measured in the alfalfa field immediately adjacent to the weighing lysimeters. These climatic and lysimeter data which are representative of the Central Great Plains were used to calibrate the modified Penman equation (15):

$$ET_o = \frac{\Delta}{\Delta + \gamma}(R_n - G) + \frac{\gamma}{\Delta + \gamma}(15.36)\, f(W)(e_s - e_d) \quad \ldots\ldots\ldots\ldots (5)$$

in which ET_o = potential evapotranspiration in langleys; Δ = the mean slope of the saturation vapor pressure-temperature curve, de/dT; γ = the psychrometric constant; e_s = the mean saturation vapor pressure, in millibars (mean of saturated vapor pressure at maximum and minimum daily air temperatures); e_d = the saturation vapor pressure at mean dew point temperature, in millibars; W = the total daily wind run, in miles, at 2 m; R_n = daily net radiation, in calories-centimeters^{-2}; G = daily soil heat flux, in calories-centimeters^{-2}; and $f(W)$ = the wind function of Penman (11).

The wind function and net radiation estimation equations were calibrated by least squares regression on the Mitchell data; whereas the daily soil heat flux was relatively small and was estimated by an empirical relationship (7). They present a procedure to estimate the daily net radiation, in calories per square centimeter, as follows:

$$R_n = (1 - \alpha)R_s - R_b \quad \ldots\ldots\ldots\ldots (6)$$

in which $(1 - \alpha)R_s$ = the net shortwave radiation received by a green crop with full cover; α = the mean daily shortwave reflectance or albedo (assumed to be 0.23); and R_b = the net outgoing long wave radiation and is estimated by

$$R_b = \left(a\frac{R_s}{R_{so}} + b\right)R_{bo} \quad \ldots\ldots\ldots\ldots (7)$$

in which R_{bo} = the net outgoing longwave radiation, in calories per square centimeter, on a clear day and estimated as follows:

$$R_{bo} = (0.31 - 0.044\sqrt{e_d})(11.71 \times 10^{-8})\frac{T2_A^4 + T1_A^4}{2} \quad \ldots\ldots\ldots\ldots (8)$$

in which 11.71×10^{-8} = the Stefan-Boltzmann constant, in calories-centimeters^{-2}-days^{-1}-degrees Kelvin^{-4}; and $T2_A$ and $T1_A$ = the maximum and minimum daily air temperatures, respectively, in degrees Kelvin.

The clear sky solar radiation, R_{so}, was determined for Mitchell by plotting the daily total solar radiation and fitting an empirical equation to the upper envelope curve for the irrigation season as:

$$R_{so} = 760 \exp\left[-\left(\frac{D - 166}{157}\right)^2\right] \quad \ldots\ldots\ldots\ldots (9)$$

in which D = the Julian day; and R_{bo} is assumed to occur on days when the measured solar radiation was at least 95% of the clear day value and was estimated for calibrating Eq. 8 by calculating R_b with Eq. 6. The intercept and slope of the first part of Eq. 8 were found to be 0.37 and −0.044, respectively. The slope is the same as reported by Jensen, et al. (7) with the intercept being 0.37 instead of 0.31. The constants are similar to those reported by Goss and Brooks (4).

In Eq. 7, the coefficients, a and b, were determined to be 0.9 and 0.1, respectively, using measured R_n and R_s data and calculated R_b, R_{bo}, and R_{so} data.

The wind function, $f(W)$, was calibrated with the measured potential ET data selected for days having at least 12 in. (30 cm) of top growth of well watered alfalfa. The resulting function is $f(W) = 1.1 + 0.017W$. The coefficient of W compares with slope of 0.018 which was found from data in Idaho (15).

Adjusting Akron Climatic Data.—Solar radiation, temperature, humidity, and wind, as required for the Penman equation, were observed at the Akron Central Great Plains Field Station from 1968-1971. However, because the Akron Station is not located in an irrigated area, the vapor pressure would be lower and the wind speeds higher than in an adjacent irrigated area. These trends in vapor pressure and wind were reported by Burman (personal communication), Davenport and Hudson (1) and deVries and Birch (2).

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$$R_{so} = 720 \exp\left[-\left(\frac{D - 165}{150}\right)^2\right] \quad \ldots\ldots\ldots\ldots (10)$$

The wind and dew point data exhibited considerable differences when compared for the two areas. The average wind speed at Akron was approx 2.2 mph (3.5 km/hr) higher than at Crook. The linear regression equation between the vapor pressure at Crook and the vapor pressure at Akron was

$$e_d(\text{CROOK}) = 0.24 + 0.843\, e_d(\text{AKRON}) \quad (11)$$

The wind was reduced 2.2 mph (3.5 km/hr) and the vapor pressure adjusted with Eq. 11. The resulting Akron and Crook potential ET had random differences

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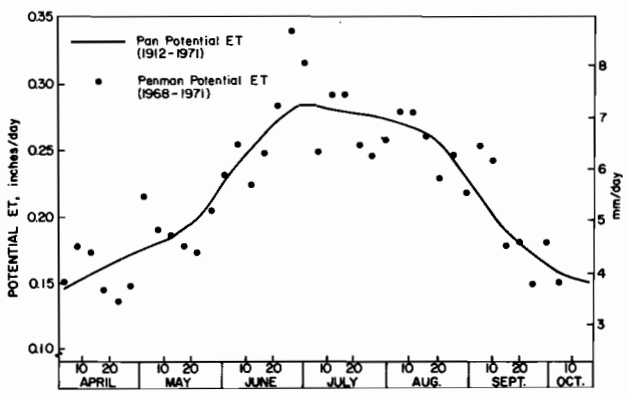
Soil water holding capacity, in inches per foot (centimeters per centimeter) (1)	Irrigation cycle, in days revolution (2)	Net irrigation, in inches per day (millimeters per day) (3)
0.75	1	0.10
(0.06)		(2.5)
1.0	3	0.15
(0.08)		(3.8)
1.5	7	0.20
(0.13)		(5.1)
2.0	14	0.25
(0.17)		(6.4)
		0.30
		(7.6)
		0.35
		(8.9)
		0.40
		(10.2)



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The vapor and wind pressures for 4 yr of Akron data were adjusted and

potential ET (for an irrigated environment) was calculated. The Penman potential ET and observed precipitation for the 4 yr were used as input for the initial simulation analysis.

Calibration of Akron Evaporation Pan.—Only 4 yr of input data for the Penman equation are available for Akron; however, BPI pan evaporation data have been observed for nearly 60 yr. The modified Penman ET, calculated with the adjusted data, was correlated with the pan evaporation data for the 4-yr period. A linear regression of the potential ET for the irrigated environment and the measured pan evaporation data for the months of June, July, and August yielded:

$$ET_o = 0.119 + 0.541\, E_p \quad (12)$$

in which ET_o = potential evapotranspiration; and E_p = BPI pan evaporation. For May and September the equation is

$$ET_o = 0.044 + 0.703\, E_p \quad (13)$$

These equations were used to estimate ET_o from the 60 yr of BPI pan evaporation recorded at Akron.

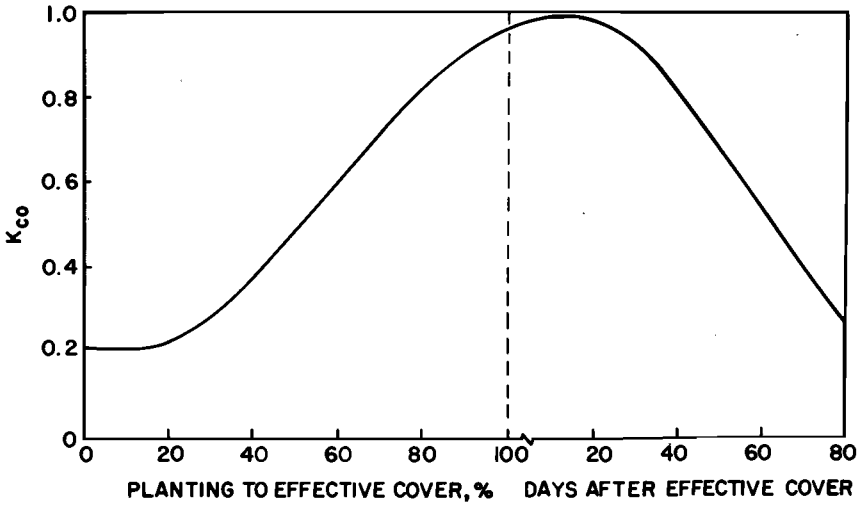
The 60-yr average potential ET as estimated from Eqs. 12 and 13 was compared with a 5-day average calculated Penman potential ET for the 1968–1971 data (Fig. 3).

Operational Options.—The system capacity and speed of operation are the two variables that must be specified by the designer of a center pivot sprinkler irrigation system. The water holding capacity of the soil and water requirements of the crop influence those design variables. Corn irrigation with variations of soil water holding capacity, irrigation cycle time, and net irrigation capacity (Table 1) was simulated. The assumed five water holding capacities, seven irrigation system capacities, and four speeds of operation resulted in a total of 140 simulations for each year of climatic data. The different net irrigation capacity and irrigation cycles provide a total of 28 irrigation depths. For example, a 0.1-in./day (2.5-mm/day) capacity system with a 1-day irrigation cycle would apply 0.1 in. (2.5 mm)/irrigation whereas the same system with a 7-day cycle would apply 0.7 in. (18-mm)/irrigation.

An irrigation depth was applied when this depth equaled the simulated soil water depletion. The frequency of irrigations, however, was limited by the irrigation cycle. The 7-day and 14-day irrigation cycles were reduced to a 3-day cycle during early stages of growth when the available water in the limited root zone was less than twice the net irrigation application.

The soil profile was assumed to be full at the start of each irrigation season. Even if this were not true, the capacity of a system would enable refilling the profile early in the season. The simulations determined the maximum depletion occuring on any day during each year. The required system capacity based on not exceeding a depletion of 40%, 50%, and 60% of the available soil water was interpolated from maximum depletions occurring with the seven chosen system capacities.

The simulation model had the option to delay an irrigation until the depletion equaled the irrigation depth plus an additional specified depth. This additional depletion depth or water holding storage capacity would enable storing some rainfall which might occur immediately after an irrigation.



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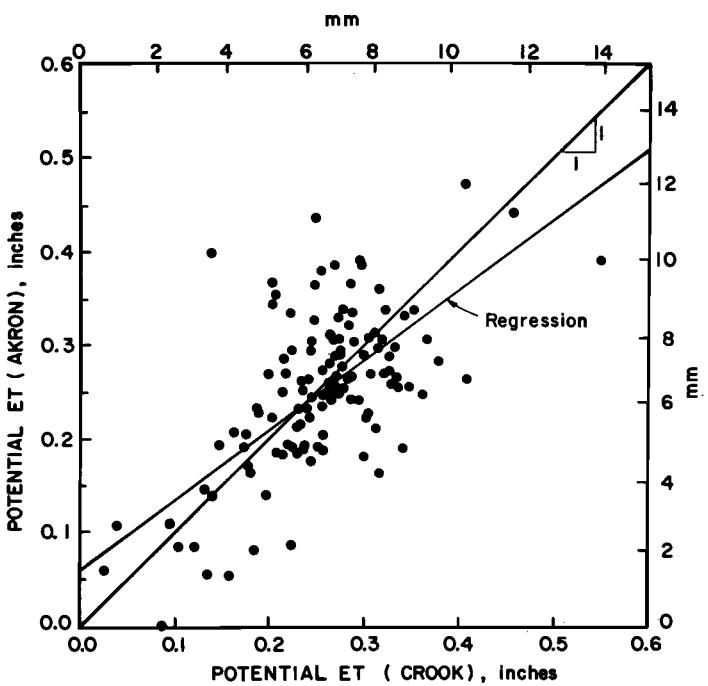

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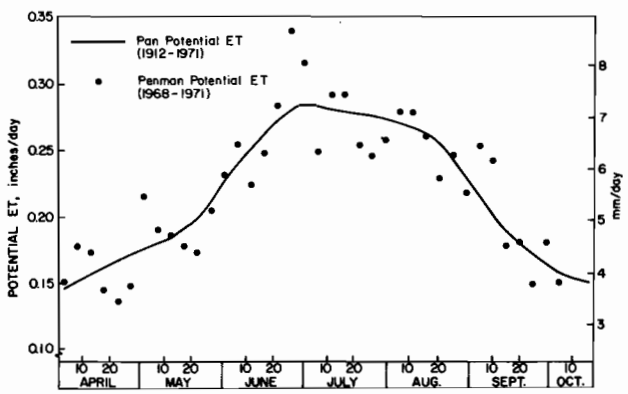

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Operational Options.—The system capacity and speed of operation are the two variables that must be specified by the designer of a center pivot sprinkler irrigation system. The water holding capacity of the soil and water requirements of the crop influence those design variables. Corn irrigation with variations of soil water holding capacity, irrigation cycle time, and net irrigation capacity (Table 1) was simulated. The assumed five water holding capacities, seven irrigation system capacities, and four speeds of operation resulted in a total of 140 simulations for each year of climatic data. The different net irrigation capacity and irrigation cycles provide a total of 28 irrigation depths. For example, a 0.1-in./day (2.5-mm/day) capacity system with a 1-day irrigation cycle would apply 0.1 in. (2.5 mm)/irrigation whereas the same system with a 7-day cycle would apply 0.7 in. (18-mm)/irrigation.

An irrigation depth was applied when this depth equaled the simulated soil water depletion. The frequency of irrigations, however, was limited by the irrigation cycle. The 7-day and 14-day irrigation cycles were reduced to a 3-day cycle during early stages of growth when the available water in the limited root zone was less than twice the net irrigation application.

The soil profile was assumed to be full at the start of each irrigation season. Even if this were not true, the capacity of a system would enable refilling the profile early in the season. The simulations determined the maximum depletion occuring on any day during each year. The required system capacity based on not exceeding a depletion of 40%, 50%, and 60% of the available soil water was interpolated from maximum depletions occurring with the seven chosen system capacities.

The simulation model had the option to delay an irrigation until the depletion equaled the irrigation depth plus an additional specified depth. This additional depletion depth or water holding storage capacity would enable storing some rainfall which might occur immediately after an irrigation.

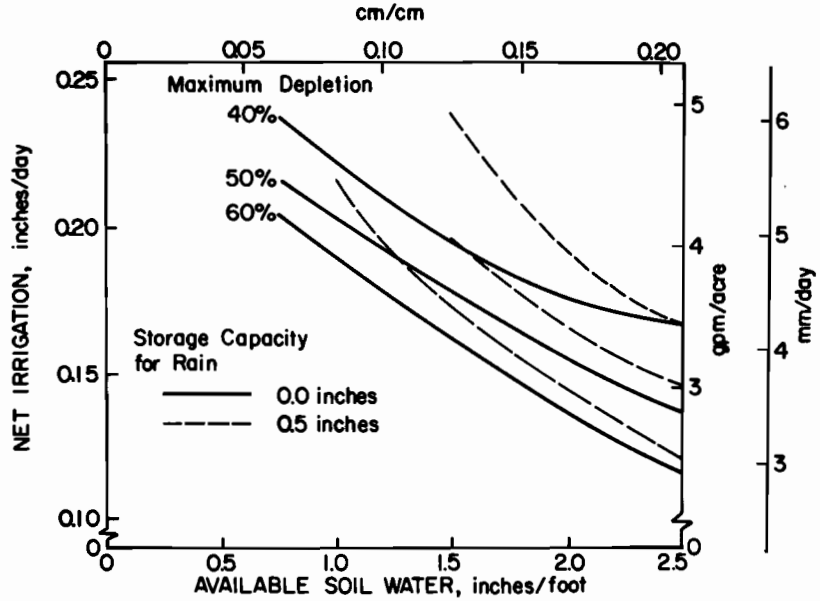


FIG. 4.—Net Irrigation for Center Pivot Systems Versus Available Soil Water is Based Upon Average of 4 yr Data or 50% Probability Level.

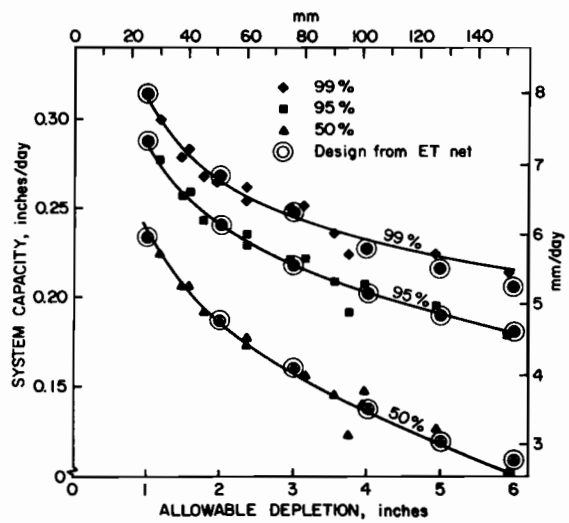


FIG. 5.—Design Irrigation System Capacity for Maintaining Depletion Below Given Level for Three Probabilities (Design Capacity Is Net Capacity and Must Be Increased for Irrigation Efficiency and Down Time)

Results

Simulation Based on Penman Estimates of Potential ET.—The simulation was first run using the 4 yr of Akron data (1968–1971) for which the modified Penman potential ET could be calculated. The average center pivot irrigation system capacities which maintained the soil water depletion above chosen levels are summarized in Fig. 4. The extraction of soil water can be kept below 50% depletion with a net irrigation of 0.22 in./day and 0.14 in./day (5.6 mm/day–3.6 mm/day) as the available soil water increases from 0.75 in./ft–2.5 in./ft (0.06 cm/cm to 0.21 cm/cm), respectively. The system capacity must be increased approx 0.025 in./day (0.65 mm/day) when the desired maximum depletion is 40%. If one permits a maximum depletion of 60%, the system capacity could be reduced approx 0.015 in./day (0.4 mm/day).

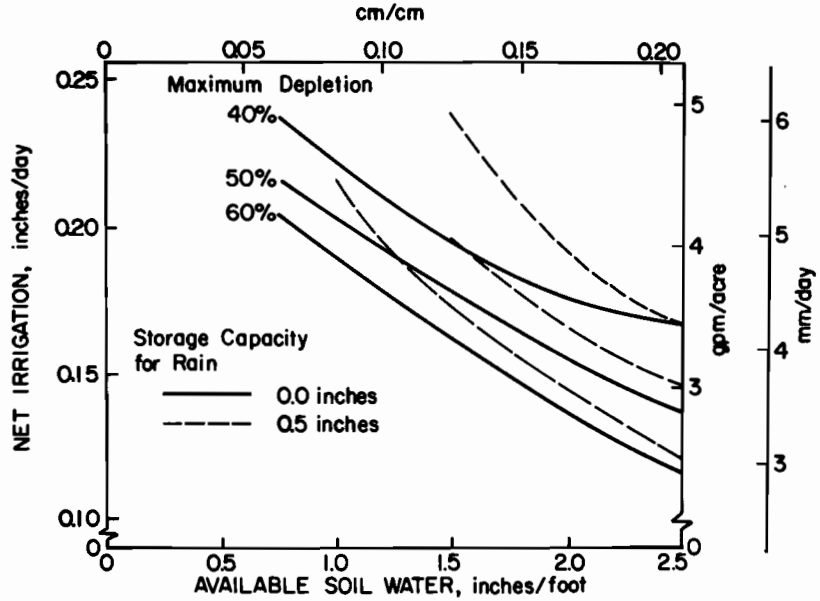
Operating with a 0.5-in. (13-mm) storage capacity for rain requires an increase in the system capacity if the allowable depletion is not to be exceeded. It is not recommended to have a 0.5-in. (13-mm) storage capacity for rain when the soil holds less than 1.5 in./ft (0.13 cm/cm) available water. Soils with the smaller water holding capacities require frequent, light irrigations. An operational procedure for maintaining the soil profile at the maximum storage capacity gives some safety for avoiding excessive soil water depletions if the system fails.

Simulation Based on Evaporation Pan Estimates of Potential ET.—The simulation was run by the use of the 60-yr data, and the results were used to develop center pivot system design capacities for different probability levels. The design system capacity required to meet the irrigation requirement is a function of the maximum allowable depletion (Fig. 5). The various symbols, representing soil water depletion levels, indicate that the difference between 40%–60% is of minor importance as compared to the probability of having sufficient capacity to replace soil water depleted. A graphical inspection of the 60 yr indicated that the probability of meeting ET follows a normal distribution. The net irrigation requirement based on the 4-yr simulation is slightly higher than that determined with the 60-yr simulation. The 50% probability level would require 0.24 in./day (6.1 mm/day) net irrigation for a maximum depletion of 1.2 in. (30 mm) but with the 60-yr simulation a 0.23-in./day (5.8-mm/day) net irrigation system capacity is sufficient.

The design system capacities are net irrigation requirements and must be increased for water application efficiencies. A 90% water application efficiency has been used successfully in scheduling the irrigation of center pivot systems. The design system capacity, however, should also be increased to allow for down time. Realistically, at least 1 day in 7 should be allowed for down time, or an increase of 17%. The design system capacity should be increased 30% above the net irrigation requirement to allow for down time and application efficiency.

The selection of the probability level would depend on the value and sensitivity of the crop. Yields for nonsensitive crops may not be significantly reduced by limited periods of soil water depletion exceeding an allowable level used for design.

The maximum depletion and the number of periods and days that the depletion exceeded the designed depletion (50% of the available water in the root zone)



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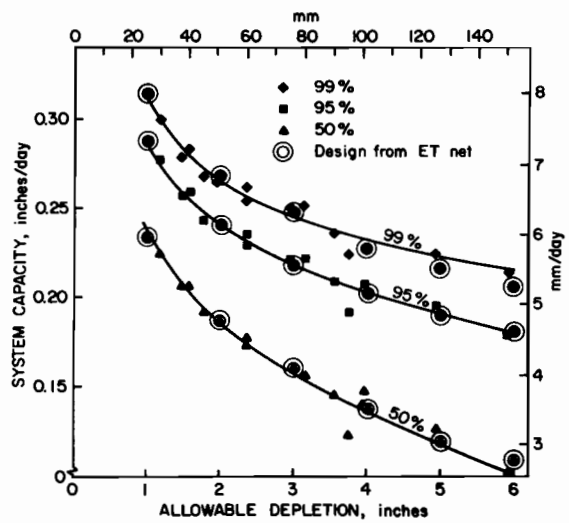

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The selection of the probability level would depend on the value and sensitivity of the crop. Yields for nonsensitive crops may not be significantly reduced by limited periods of soil water depletion exceeding an allowable level used for design.

The maximum depletion and the number of periods and days that the depletion exceeded the designed depletion (50% of the available water in the root zone)

TABLE 2.—Summary of Simulated Depletions for Example System Designs for Years When 50% Depletion Was Exceeded

Year (1)	Available soil water, in inches per foot (centimeters per centimeter) (2)	Net irrigation capacity, in inches per day (millimeters per day) (3)	Maximum depletion, as a percentage (4)	Periods (5)	Days (6)
1939	0.75 (0.06)	0.25 (6.4)	51	1	1
1940	0.75 (0.06)	0.25 (6.4)	54	1	11
1960	0.75 (0.06)	0.25 (6.4)	59	3	15
1919	1.5 (0.13)	0.20 (5.1)	54	5	6
1924	1.5 (0.13)	0.20 (5.1)	52	2	2
1934	1.5 (0.13)	0.20 (5.1)	55	4	6
1935	1.5 (0.13)	0.20 (5.1)	53	4	4
1939	1.5 (0.13)	0.20 (5.1)	51	2	2
1940	1.5 (0.13)	0.20 (5.1)	73	5	34
1952	1.5 (0.13)	0.20 (5.1)	62	7	28

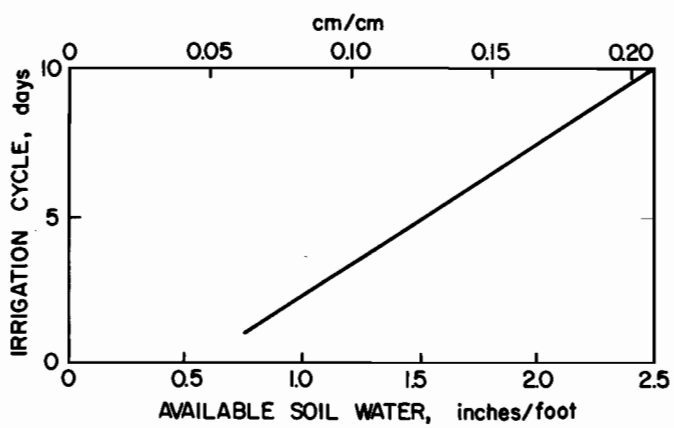

FIG. 6.—Recommended Maximum Cycle as Limited by Available Soil Water.

were included in the output for each year simulated (Table 2). In the first example [0.75 in./ft (63 mm/m) of available soil water and 0.25 in. (6.4 mm)/day net irrigation capacity], the soil water depletion has a 78% and 96% probability of not exceeding 40% and 60% depletion, respectively. In the 60 yr simulated, only 3 yr had soil water depletions greater than 50% with none exceeding the 60% depletion level. The second example [1.5 in./ft (130 mm/m) of available soil water and 0.20 in. (5 mm)/day net irrigation capacity] has a 60% and 91% probability of not exceeding 40% and 60% depletion, respectively. In the 60 yr simulated, 7 yr had soil water depletions greater than 50% with 1 having a maximum depletion of 73%.

Recommended maximum cycle times (Fig. 6) for the recommended design capacities are based on not exceeding a 50% allowable depletion. Longer cycle times could be satisfactorily used in some years, but in some of the simulated years large depletions resulted. The assumption is that the intake capacity is equal to or larger than the application depth.

General Design Consideration.—The average rainfall for May 1-September 30 is 11.4 in. (290 mm). Since the same rainfall is expected from Julesburg to Burlington, Colo., the recommended design system capacities could be applied to northeastern Colorado, western Nebraska, and western Kansas. The simulation indicated that approx 60% of the total rainfall would not be lost to runoff or deep percolation when the soil has a water holding capacity of 0.75 in./ft (0.06 cm/cm). The estimated use of rainfall increases from 60%-80% as the available water holding capacities increase to 2.5 in./ft (0.21 cm/cm). The use of rainfall could be increased approx 5%-10% by operating with a 0.5-in. (13-mm) storage capacity when soil water holding capacities exceed 1.5 in./ft (0.13 cm/cm).

The simulation was limited to corn; however, other crops would have similar design system capacities for center pivots since the peak potential ET and the peak water use period for most common crops grown in this area nearly coincide. Only the operation of the system would be significantly affected when irrigating alfalfa, sugarbeets, or beans.

Design system capacities can be decreased as the available soil water holding capacity increases because the allowable depletion depth also increases (Fig. 5). In general, the intake capacity decreases on soils with larger water holding capacities. Smaller capacity systems reduce application rates and help minimize runoff problems but can still maintain allowable depletion levels. Field experience has shown that longer cycle times allow the surface to dry and form cracks which increases the initial intake rate and intake capacity. It may be necessary to start the first irrigation before the soil has been depleted to the design level. Otherwise, a large soil water depletion may result by the end of the irrigation cycle. It may be advisable to initially run the system fast and then gradually slow it down during the first cycle.

Design with Potential ET Probabilities.—Design system capacities were developed by simulations of irrigations. Irrigation designs are generally not made with simulations but use peak water requirements. This section compares the design with simulation versus that using peak water requirements. The frequency distribution for daily average potential ET and accumulative frequency distribution for 1-day-30-day values were developed (Figs. 7 and 8) similar to those presented by Pruitt, et al. (8), Nixon, et al. (9), and Wright and Jensen (11).

The potential ET does not take into consideration the stage of growth as used in the simulation model. The crop coefficients for the June 24–July 23 period were 0.945, 0.933, 0.920, and 0.890 for 3-day, 7-day, 14-day, and 21-day periods. The dashed curves (Fig. 9) are the cumulative distribution functions

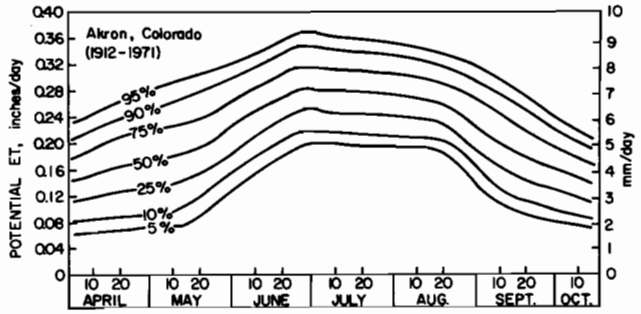

FIG. 7.—Frequency Distributions for Estimated Daily Maximum Potential ET as Estimated by BPI Pan for Akron, Colo. (1912–1971)

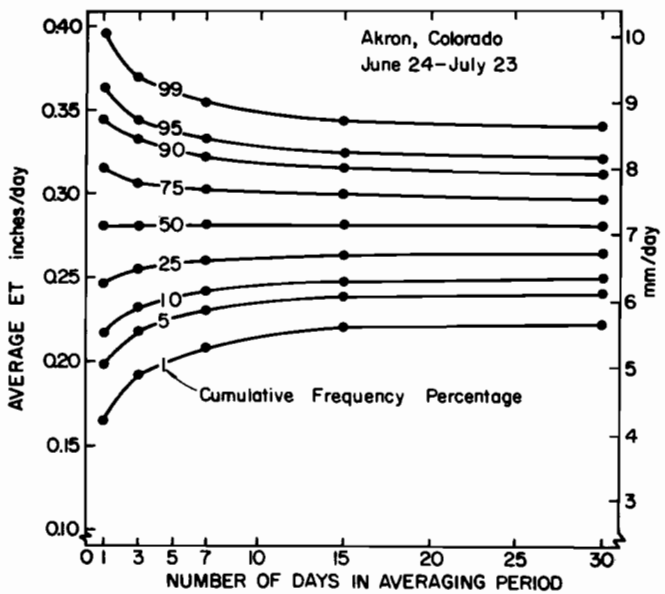

FIG. 8.—Cumulative Frequency of 1-day through 30-day Mean Daily ET Rate for Peak Period (June 24–July 23) for Akron, Colo.

of mean daily ET rates adjusted with the appropriate crop coefficients. Subtracting the amount of rainfall, R, expected at the same probability level results with the line-dash-line curve (3). This subtraction has no theoretical basis, therefore, the ET-R curve does not have the same probability as the ET and R have individually.

TABLE 3.—Empirical Procedure for Determining Net Irrigation Requirement Versus Allowable Depletion from Cumulative Frequency Distribution of ET_{net} for Akron, Colo.

Allowable depletion, in inches (millimeters) (1)	P = 50%			P = 95%			P = 99%	
	Return period, in days (2)	ET_{net}, in inches per day (3)	Adjusted rate,[a] in inches per day (4)	Return period, in days (5)	ET_{net}, in inches per day (6)	Adjusted rate,[b] in inches per day (7)	ET_{net}, in inches per day (8)	Adjusted rate,[b] in inches per day (9)
1 (25)	1/2	0.245	0.235	3.5	0.308	0.288	0.355	0.315
2 (51)	7	0.207	0.187	14	0.271	0.241	0.299	0.269
3 (76)	14	0.191	0.161	21	0.260	0.220	0.288	0.248
4 (102)	21	0.178	0.138	28	0.252	0.202	0.278	0.228
5 (127)	28	0.170	0.120	30	0.251	0.191	0.276	0.216
6 (152)	30	0.169	0.109	30	0.251	0.181	0.276	0.206

[a]Adjusted rate = ET_{net} (days) − 0.01 × Allowable depletion.
[b]Adjusted rate = ET_{net} (days) − 0.01 × Allowable depletion − 0.01.

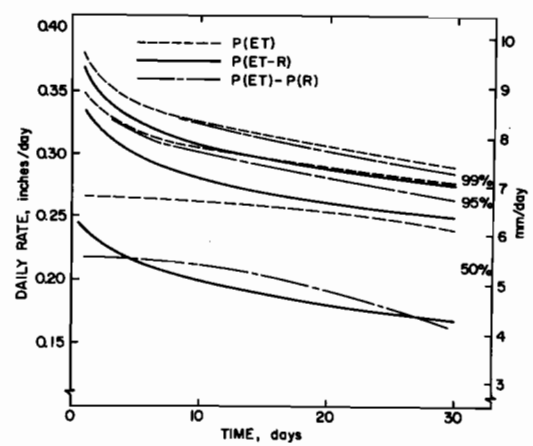

FIG. 9.—Cumulative Frequency of 1-day through 30-day: Average Daily ET Rate; Mean Daily ET Rate Minus Probable Daily Rainfall Amount; and Probable Daily ET minus Rainfall Rate for Peak Period (June 24–July 23) for Akron, Colo.

The distribution function for daily net ET $[F_{et}(z)]$ can be obtained from the distribution functions for daily ET $[H_E(e)]$ and daily rainfall $G_R(r)$. The assumption is made that both daily ET and rainfall are independently identically distributed for the peak ET month period. If E and R are independent, the cumulative distribution function for z is

$$F_{ET_n}(z) = P(E - R \leq z) = 1 - \int_0^\infty G_{R_n}(e - z)\, d\, H_{E_n}(e) \quad \ldots\ldots\ldots\ldots \quad (14)$$

in which $G_{R_n}(\cdot)$ and $H_{E_n}(\cdot)$ = the distribution functions on n-day rainfall and n-day ET, respectively (10). The convolution of the distribution functions (Eq. 14) was determined graphically with the results of the cumulative frequency shown as solid curves (Fig. 9). The frequency distribution of the daily net ET is less than ET by 0.02 in./day (0.5 mm/day), 0.025 in./day (0.6 mm/day), and 0.06 in./day (1.5 mm/day) for the 99%, and 95%, and 50% probabilities, respectively.

The design system capacity from the simulation results (Fig. 5) are less than that indicated by the frequency distribution of daily net ET. The difference can be attributed to the available storage or amount that can be used from storage in the soil root zone.

An empirical technique of determining the net irrigation system capacity from daily net ET in the Akron area is illustrated in Table 3. The time period, in days, for determining a daily rate are less for the 50% probability level than for the 95% and 99% probability levels (Table 3). The ET net rates determined from Fig. 9 at the time periods listed are reduced by 1% of the allowable depletion. An additional 0.01 in./day decrease in net irrigation requirements is made for the 95% and 99% probability levels. The circled symbols in Fig. 5 compare the net daily rates determined empirically from ET net with those determined with the simulation model. The equations for adjusting ET_{net} are shown as footnotes under Table 3.

The shorter periods and smaller reductions for the 50% probability occur since the soil water depletion at the start of any time period would be expected to be larger than for the 95% and 99% probability levels. The amount of soil water which can be depleted under different climatic conditions was not determined but could be expected to have similar trends to the empirical results for Colorado. The technique for developing net irrigation system capacities by simulation includes the use of water from storage in the soil.

Summary and Conclusions

Design system capacities were developed for center pivot sprinklers irrigating corn in the Central Great Plains by simulating irrigations for 60 yr of climatic data collected at Akron, Colo. The system design (Fig. 5) provides three probability levels of net irrigation requirements versus optimum soil water depletion as affected by soils with various water holding capacities.

The design system capacities developed from the simulation model allow for the depletion of available soil water. An empirical procedure for determining the net system capacity from ET_{net} as affected by allowable depletion levels is presented (Table 3).

Acknowledgment

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10588 CENTER PIVOT SPRINKLERS IN EASTERN COLORADO

KEY WORDS: **Climatic data;** Corn; Design; **Evaporation; Evapotranspiration; Irrigation;** Lysimeters; **Simulation; Sprinklers**

ABSTRACT: Design system capacities were developed for center pivot sprinklers irrigating corn in the Central Great Plains by simulating irrigations for 60 yr of climatic data collected at Akron, Colo. The modified Penman equation for estimating potential ET for alfalfa as a reference crop was calibrated with lysimeter and meteorological data collected at the University of Nebraska, Scottsbluff Station. The Akron, Colo., data were adjusted to represent an irrigated environment by correlating with data collected at a weather station between three center pivot sprinkler systems. The design system capacities developed from the simulation model allow for the depletion of available soil water. An empirical procedure for determining the net system capacity from ET_{net} as affected by allowable depletion levels is presented in Table 3.

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