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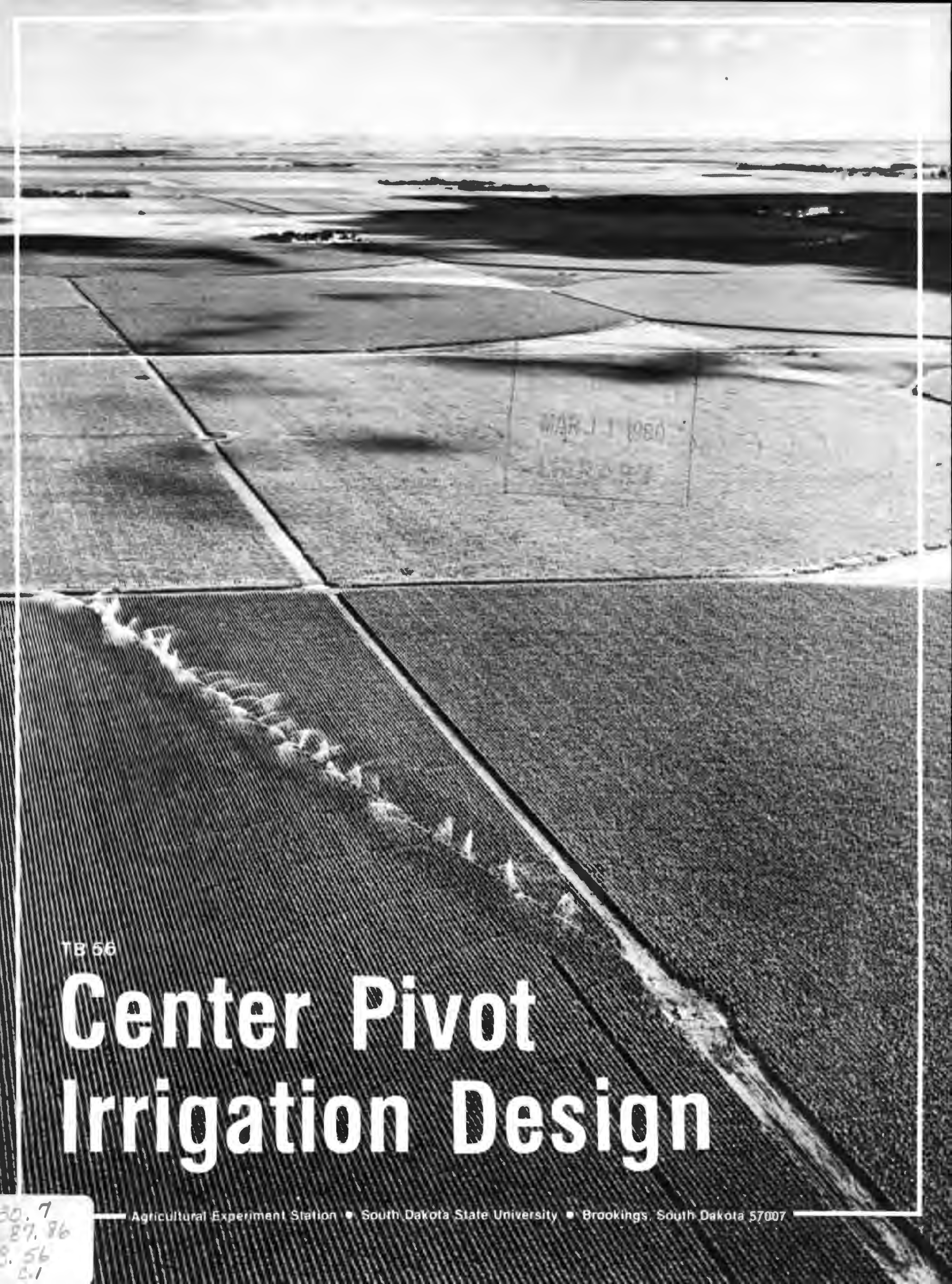
Center Pivot Irrigation Design

S.T. Chu



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Center Pivot Irrigation Design

S. T. Chu, Associate Professor, Agricultural Engineering

1. Introduction

This article describes some technical aspects of irrigation by center pivot systems. It is developed from the accumulated experience in lecturing several irrigation courses at the Department of Agricultural Engineering, South Dakota State University. Two specific problems are of general interest in the planning and design of center pivot systems. They are:

1. How to find an acceptable application rate of a center pivot system for a given soil and ground surface condition.
2. How to select sprinklers on a center pivot system for re-nozzling of system design.

The solution to these problems is to be presented from an analytical viewpoint.

The content of this article can be divided into two parts. The first four sections provide basic knowledge in center pivot irrigation and the last section describes the application of the basic knowledge in the system design. Unnecessary theoretical derivations are neglected and plenty numerical examples are illustrated to that much practical information can be included.

The material is prepared for students, engineers and personnel in extension or marketing of irrigation equipment. It is the first attempt of the writer to summarize the techniques in the design of center pivot systems. Crudeness in both theory and application are unavoidable. It is intended that this article be served as a starting point from which improved analysis may be developed in the future.

I am in debt to my colleagues in the Agricultural Engineering Department at South Dakota State University for their assistances, to Mr. Leroy Cluever for his valuable suggestions, to Drs. Darrell W. DeBoer and Charles Ullery for their reviews and comments and to Mrs. Darlene Hofer and Leanne Siebert for typing the manuscript.

2. Center Pivot Irrigation System

A center pivot system consists of a pipeline with sprinklers. The pipeline (lateral) is supported by steel frameworks (towers) spaced along the lateral. The towers are mounted on wheels, enabling the system to rotate around a pivot point. Water pumped from the well is delivered to the pivot and into the lateral through a supply pipeline.

The lateral of a typical center pivot system is about 1,300 feet long, but varies with the size of the field. An end gun is sometimes found on the end of the lateral (downstream end). The irrigated area covered by a typical system is circular in shape and is approximately 130 acres in size.

The water delivered by the system covers only a small part of the entire irrigated area at any one time. The lateral completes its circular sweep around the pivot in a period of 3 or 4 days. Various components of a center pivot system are shown in a schematic diagram (Figure 1).

A center pivot system is one of three types, based upon the arrangement and size of sprinklers.

The constant spacing system consists of a sequence of small to large sprinklers spaced equal distances apart. Variable spacing systems include a collection of medium sized sprinklers arranged at uneven intervals. The spray mist system is similar to the variable spacing system except spray nozzles are used instead of sprinklers.

The water coverage of these systems is illustrated schematically in Figure 2. A comparison of the properties of the three types of systems is summarized in Table 1.

3. Plant, Water and Soil Relationships

Irrigation is the process of supplying water to the soil. Three basic elements are involved in the process: plants, soil, and water. A study of the relationships among these elements provides the principles in irrigation planning.

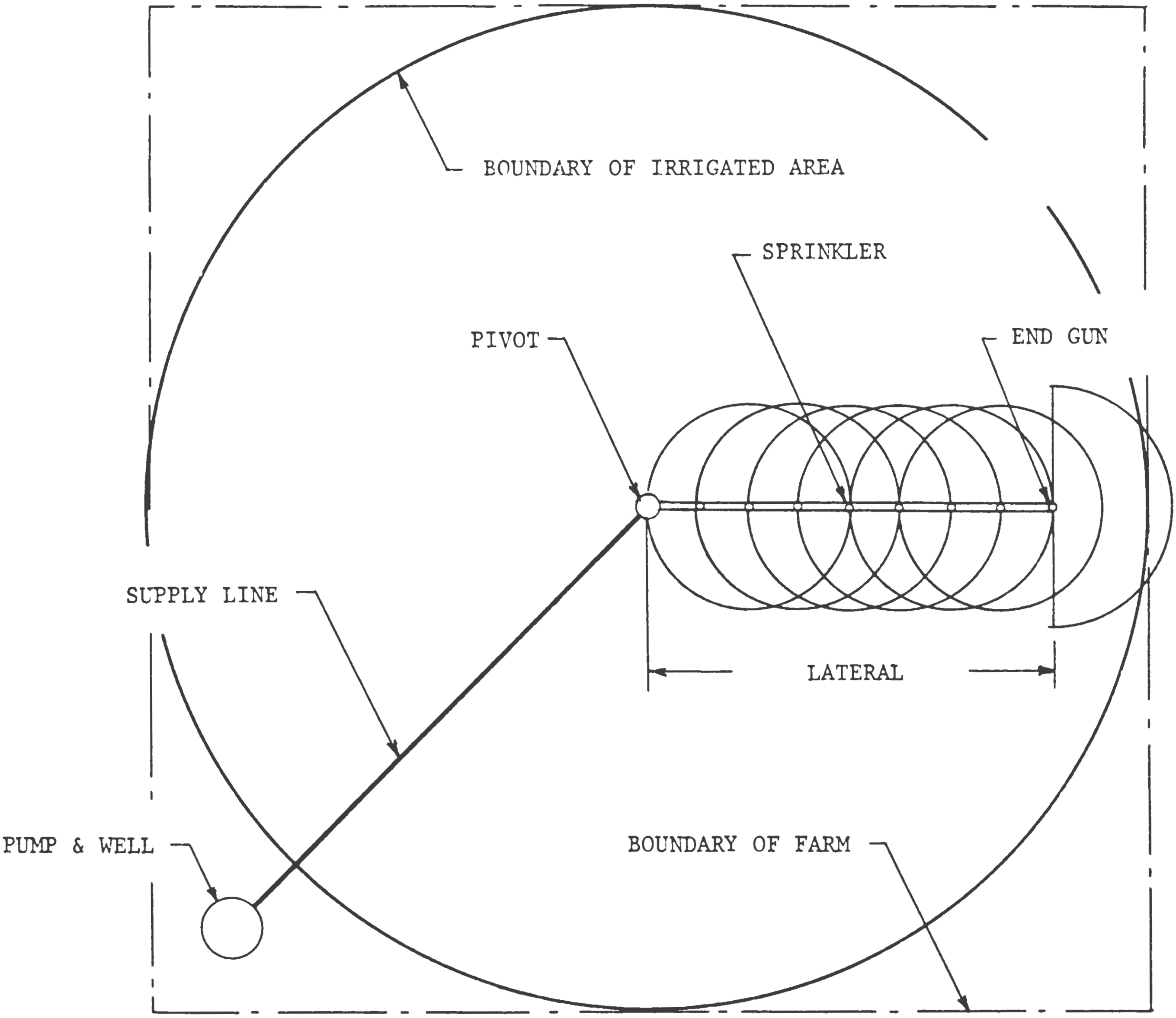
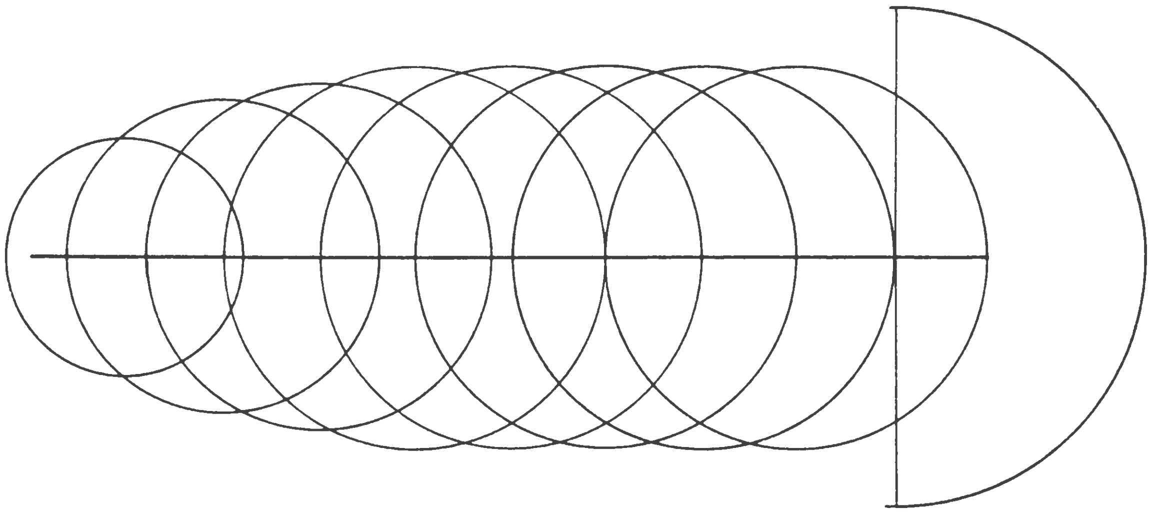
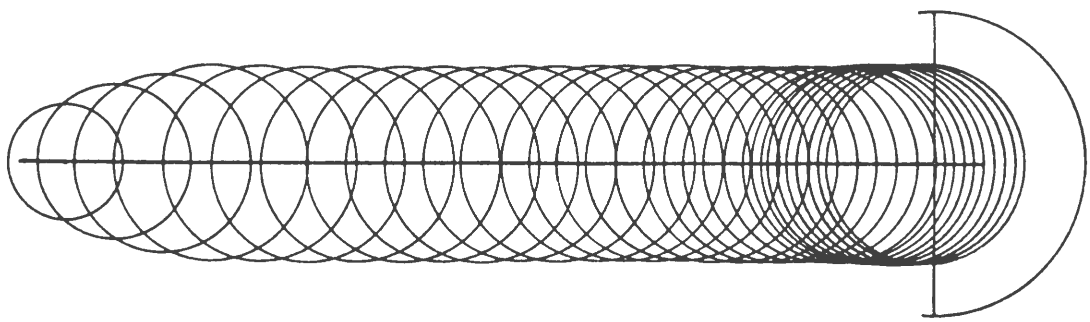


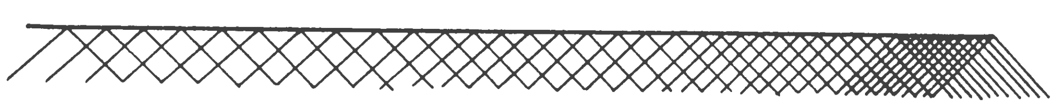
FIGURE 1: CONPONENTS OF A CENTER PIVOT IRRIGATION SYSTEM



CONSTANT SPACING SYSTEM



VARIABLE SPACING SYSTEM



SPRAY NOZZLE SYSTEM

FIGURE 2: THREE TYPES OF CENTER PIVOT SYSTEMS

TABLE 1 PROPERTIES OF THREE TYPES OF CENTER PIVOT SYSTEM.

TYPE	CONSTANT SPACING	VARIABLE SPACING	SPRAY MIST
Spacing	Constant	Variable	Variable
Sprinkler Size	Large	Medium	Small
Sprinkler	Variable	Relatively Constant	Relatively Constant
Sprinkler Coverage	Wide	Medium	Narrow
Pressure	High	Medium	Low
Cost	Relatively High	Relatively Low	Relatively Low
Energy Requirement	High	Medium	Low

3.1 Plant

The plant properties which are most important to irrigation are the root zone depth and the amount of evapotranspiration during the growing season.

3.1-1 Root zone depth

The root zone depth varies from 1 to 4 feet for different plants. All the plant's nutrient and water supply come from the feeder roots. It is unnecessary to irrigate beyond these feeder roots except in the spring or when irrigation is used to establish a fully moistened soil profile. Average root zone depth for selected crops are shown in Table 2.

TABLE 2. PLANT ROOT ZONE DEPTHS (Gray, 1957)

CROP	ROOT ZONE DEPTH IN FEET
Alfalfa	3-3.5
Beans	2
Beets	2-3
Corn	2.5
Grain	2-2.5
Potatoes	2

3.1-2 Evapotranspiration

Soil moisture may reach the atmosphere by direct evaporation from the soil, or by transpiration through the plant. The combined process of these two mechanisms is referred to as evapotranspiration. In the planning of irrigation, evapotranspiration is different from water evaporation from the surface of wet leaves, wet ground and water drops in the air. This is referred to as evaporation loss.

3.1-3 Blaney-Criddle Formula

The Blaney-Criddle formula (SCS, 1967) is frequently used to estimate the monthly evapotranspiration that

$$ET = K_t \cdot K_c \cdot \frac{t \cdot p}{100} \qquad ---- (1)$$

Where ET is the monthly evapotranspiration in inches,

t is the monthly mean air temperature in ^{o}F,

$K_t = 0.0173 \cdot t - 0.314$, a climatic coefficient associated to the mean air temperature,

K_c is a coefficient reflecting the growth stage of crop (values of K_c are obtained from Fig. 3).

p is the monthly daylight hours expressed as a percentage of the annual daylight hours. Values of p are obtained from Table 3.

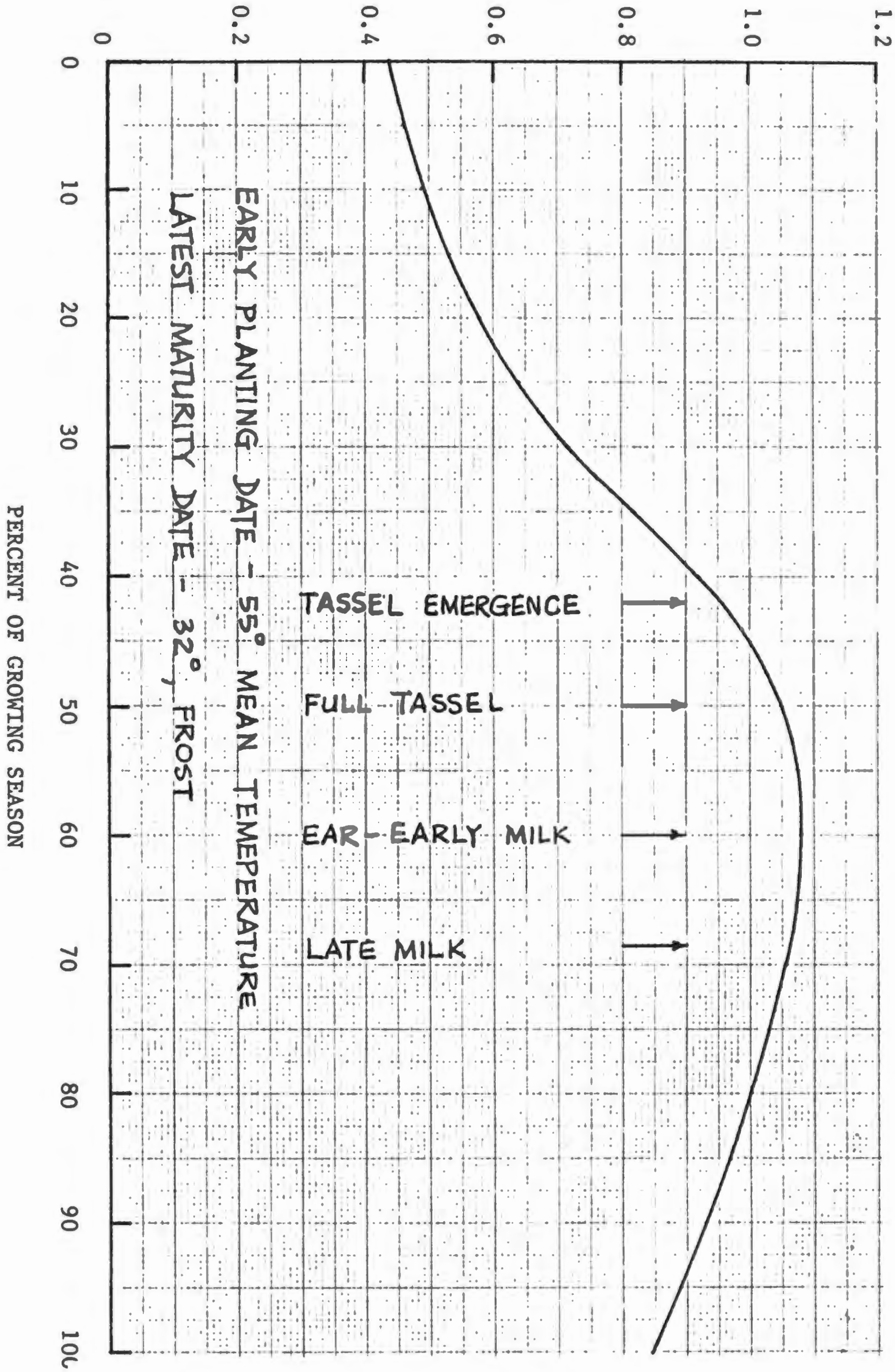


FIGURE 3: CROP GROWTH STAGE COEFFICIENT FOR CORN (GRAIN)

SOURCE: SOIL CONSERVATION SERVICE, TECHNICAL RELEASE NO. 21, 1970

Example 1: Estimate the monthly evapotranspiration for corn in Brookings, South Dakota.

Input information:

Latitude at Brookings: 44° 19"

Normal growing season at Brookings: May 15 - September 15.

Calculations:

Month	May	June	July	August	September
t, from weather data	56.4	66.0	71.5	69.6	60.2
K_t=0.0173 t -C.314	0.66	0.83	0.92	0.89	0.73
p, estimated from Table 2	10.27	10.41	10.52	9.72	8.41
Growth stage*	0.0 to 0.13	0.13 to 0.37	0.37 to 0.63	0.63 to 0.88	0.88 to 1.00
K_c, estimated from Figure 3	0.48	0.66	1.02	1.03	0.91
monthly ET**, inches	1.83	3.76	7.06	6.20	3.36
Average daily ET, inches***	0.06	0.13	0.23	0.20	0.11

* Total growing season from May 15 - September 15 is 123 days. The growing period in May (May 15 - May 31) is 16 days. The growth stage at the end of May is thus 16/123 = 0.13.

** By Blaney-Criddle formula, monthly ET in May is 0.66 (.48) 56.4 (10.27)/ 100 = 1.83 inches.

*** Number of days in May is 31, so the average daily ET in May is 1.83/31 = 0.06 inches.

Table 3. MONTHLY PERCENTAGE OF DAYLIGHT HOURS OF THE YEAR (SCS, 1967)

Latitude °N	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
50	5.99	6.32	8.24	9.24	10.68	10.92	10.99	9.99	8.46	7.04	6.08	5.65
48	6.17	6.41	8.26	9.17	10.52	10.72	10.81	9.89	8.45	7.51	6.24	5.85
46	6.33	6.50	8.28	9.11	10.38	10.53	10.65	9.79	8.43	7.58	6.37	6.05
44	6.48	6.57	8.29	9.05	10.25	10.39	10.49	9.71	8.41	7.64	6.50	6.22
42	6.61	6.65	8.30	8.99	10.13	10.24	10.35	9.62	8.40	7.70	6.62	6.39
40	6.75	6.72	8.32	8.93	10.01	10.09	10.22	9.55	8.39	7.75	6.73	6.54
38	6.87	6.79	8.33	8.89	9.90	9.96	10.11	9.47	8.37	7.80	6.83	6.68
36	6.98	6.85	8.35	8.85	9.80	9.82	9.99	9.41	8.36	7.85	6.93	6.81
34	7.10	6.91	8.35	8.80	9.71	9.71	9.88	9.34	8.35	7.90	7.02	6.93
32	7.20	6.97	8.36	8.75	9.62	9.60	9.77	9.28	8.34	7.95	7.11	7.05
30	7.31	7.02	8.37	8.71	9.54	9.49	9.67	9.21	8.33	7.99	7.20	7.16

3.2 Soil

Soil properties which greatly influence irrigation are available water holding capacity, infiltration rate, and surface retention capacity. The available water holding capacity of the root zone indicates the amount of soil moisture which crops can use. The infiltration rate and the surface retention capacity determine how much water can be applied without causing runoff.

3.2-1 Available water holding capacity

Moisture holding capacity is the amount of moisture that can be stored in soil. Heavy textured clays hold more moisture than light sandy soil.

A certain portion of the moisture held by soil is not available for plant growth. The attraction between moisture and soil is greater than between moisture and plant roots. This portion unavailable for plant use is referred to as the amount of moisture held at wilting point. Wilting point is the soil moisture at which the plant begins to wilt. The rest is available soil moisture. Holding capacity for different types of soils are shown in Table 4.

TABLE 4: WATER HOLDING CAPACITY FOR VARIOUS SOILS (Gary, 1957)

SOIL TYPE	WATER HOLDING CAPACITY inches/foot	AMOUNT HELD IN SOIL AT WILTING POINT inches/foot	AVAILABLE SOIL MOISTURE inches/foot
Sandy	1.25	0.25	1.00
Medium	2.25	0.56	1.69
Heavy	3.67	1.28	2.39

3.2-2 Infiltration rate and surface pondage

Infiltration is water entering the soil. The infiltration rate depends on soil type and the amount of water already stored in the soil. Infiltration rate on sandy soils is usually greater than on heavy soils. The first inch of water enters into the soil at a faster rate than the following inches.

The variation of the infiltration rate can be described by the Green and Ampt equation (Green and Ampt, 1911) that

$$f = K\ (1 + SM/F) \qquad \text{- - - - (2)}$$

where f is the infiltration rate in inches per hour,

K is the hydraulic conductivity of the wetted zone in inches per hour,

SM is the soil characteristic associated with moisture content and soil moisture tension,

F is the cumulative infiltration.

K and SM are needed to determine whether the application rate of a center pivot system is acceptable. The Soil Conservation Service has classified soils into several soil intake families; soil characteristics associated with each family, evaluated by Chu (1977), are listed in Table 5.

TABLE 5: SOIL CHARACTERISTICS FOR VARIOUS SOIL INTAKE FAMILIES

SOIL	SOIL INTAKE FAMILY	K INCHES PER HOUR	SM INCHES
Clay loam	0.3	0.09-0.26	1.70-2.40
Silt loam	0.5	0.26-0.55	1.40-1.70
Sandy loam	1.0	0.55-1.05	1.05-1.40

Surface pondage results when application rate is greater than the infiltration rate. Surface pondage depends on the application rate and pattern and the amount of applied water. Dillon et al. (1972) suggested that the rate-time relationship of the applied water under a center pivot system can be represented by an elliptical pattern. Surface pondage under an elliptical pattern is described in Fig. 4

3.2-3 Allowable application rate and surface retention capacity

The Soil Conservation Service (1978) has carried out sprinkler irrigation tests on various soils to study maximum application rate. These tests were conducted under a constant application pattern.

TABLE 6: MAXIMUM SPRINKLER APPLICATION RATE (ALLOWABLE RATE), IN/HR, FOR CROPS WITH COVER (SCS, 1978)

SOIL	SOIL INTAKE FAMILY	LAND SLOPE	NET APPLICATION 0.5"	1.0"	1.5"
Clay	0.3	2% or less	2.00*	0.90-1.50	0.55-1.00
		2-5%	1.60-2.00	0.65-1.10	0.50-0.85
		over 5%	1.50-1.80	0.55-0.95	0.40-0.75
Silt loam	0.5	2% or less	2.00	1.50-2.00	1.00-1.85
		2-5%	2.00	1.10-2.00	0.85-1.70
		over 5%	1.80-2.00	0.95-2.00	0.75-1.50
Sandy loam	1.0	2% or less	2.00	2.00	1.85-2.00
		2-5%	2.00	2.00	1.70-2.00
		over 5%	2.00	2.00	1.50-2.00

* 2.00 considered as highest practical rate for design or operation of system. For bare ground or row crops, use 2/3 of the value listed in the table.

There is a maximum amount of water which can be held on the soil surface without causing runoff. This amount is the surface retention capacity. If the surface pondage is less than the retention capacity, runoff will not occur. Surface pondage under allowable application rate equals the retension capacity. The relationship between the retention capacity and the allowable application rate is described in figure 5. Figures 4 and 5 are the basic information needed to determine whether the application rate of a center pivot system is acceptable.

3.3 Water

3.3-1 Gross depth of application

How much water is to be applied? The amount of water applied per irrigation is the gross depth of application. Water applied by a sprinkler system is subjected to evaporation loss from the surface of wet leaves, the wet ground and water drops traveling through the air. Such loss is estimated to be one quarter of an inch per irrigation. The gross depth of application is recommended to be not less than one inch, otherwise a large portion of the water is lost by evaporation.

Even when the irrigated water reaches the soil profile, it is subjected to further losses due to deep percolation and uneven distribution.

When the evaporation and deep percolation losses are deducted from the gross depth of application, the remaining part is called the net depth of application. The application efficiency is defined as

$$e_a = D_n / D_G \qquad \text{- - - - (3)}$$

where e_a is the application efficiency,

D_n is the net depth of application in inches,

D_G is the gross depth of application in inches.

The net depth of application is usually set to be 1.0 inch for center pivot irrigation. A larger net depth may cause runoff.

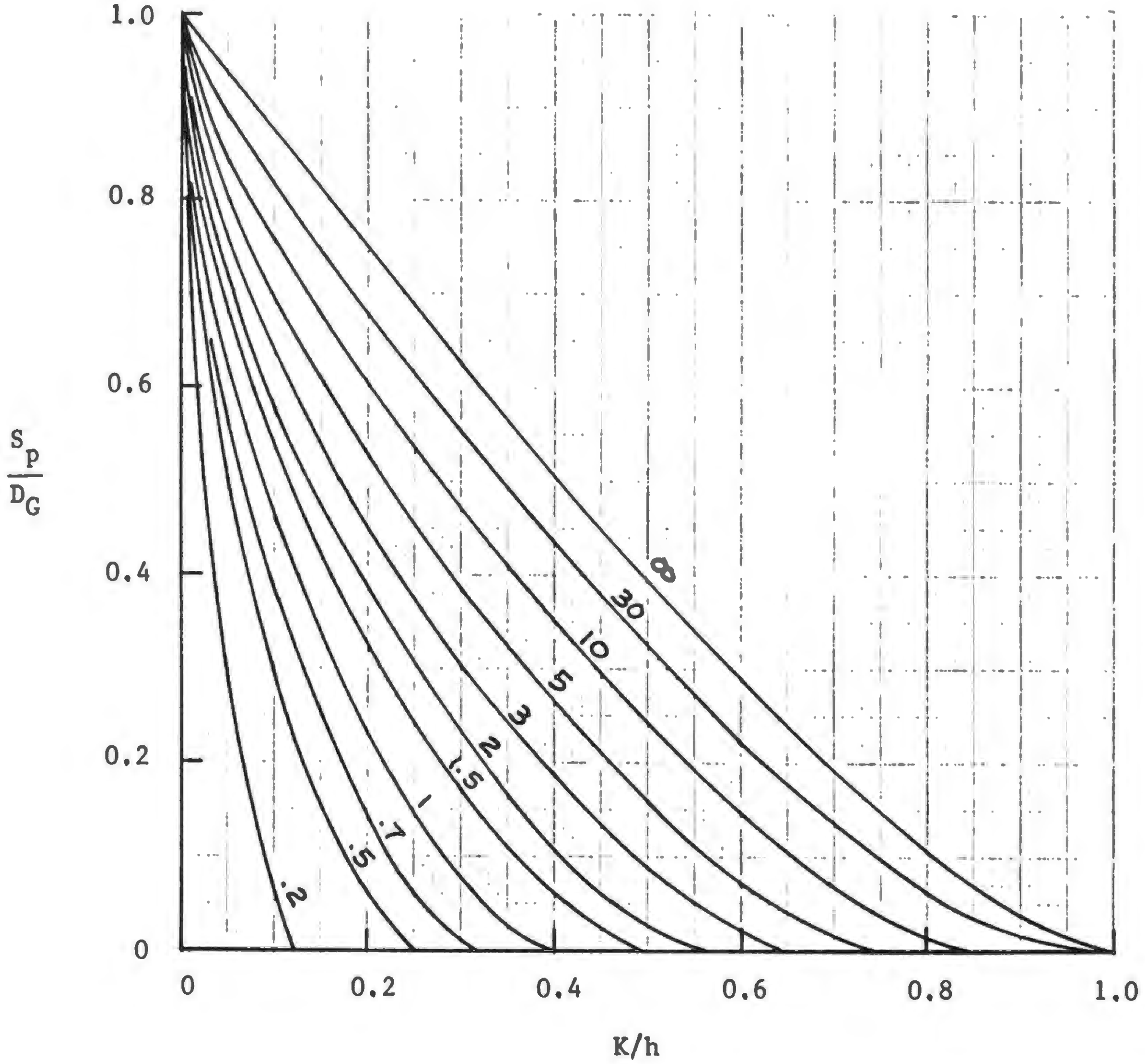


FIGURE 4: SURFACE PONDAGE UNDER AN ELLIPTICAL APPLICATION PATTERN
(NUMBERS ON CURVES ARE VALUES OF D_G/SM)

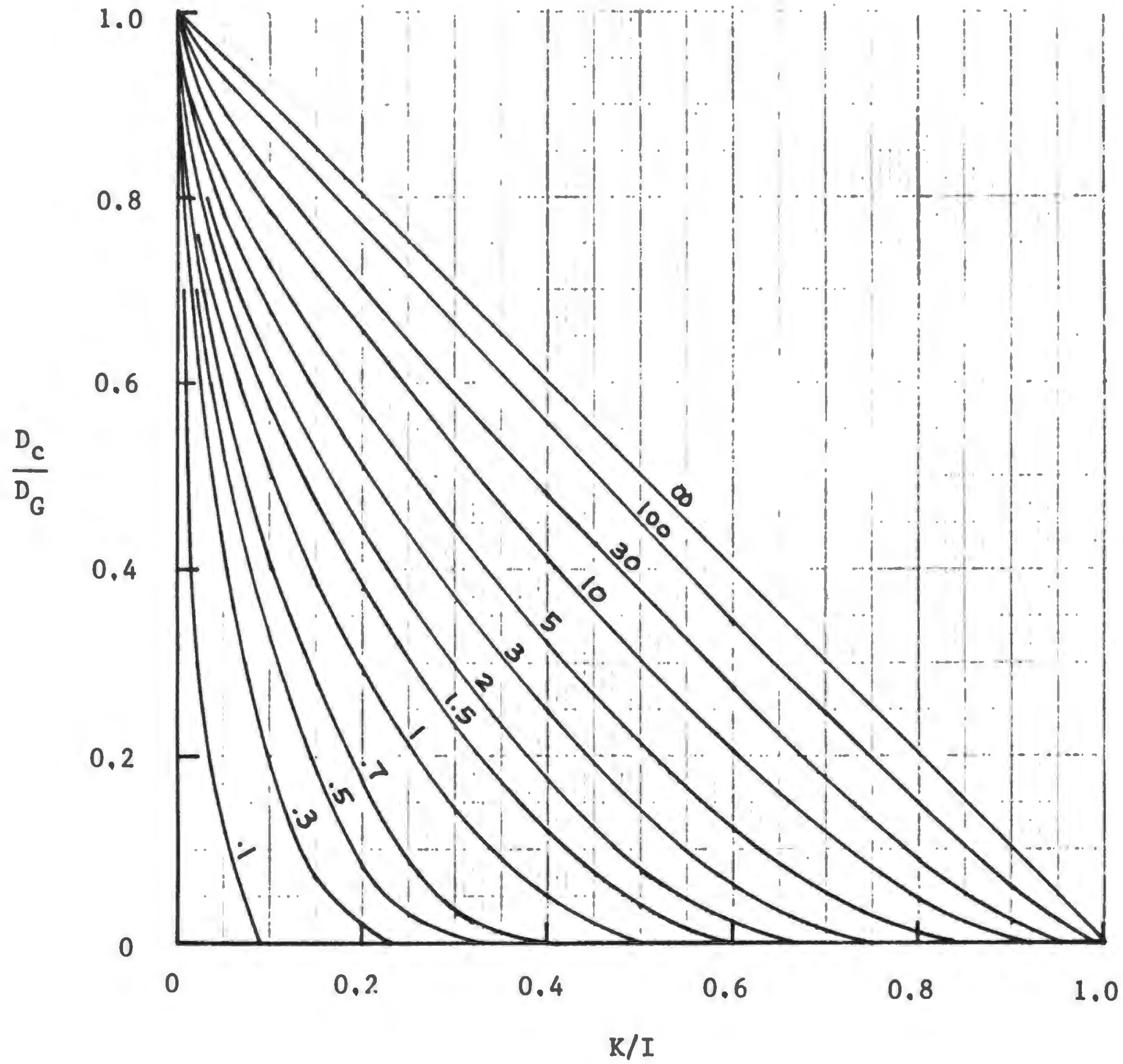


FIGURE 5: DETENTION CAPACITY UNDER A CONSTANT APPLICATION PATTERN

(NUMBERS ON CURVES ARE VALUES OF D_G/SM)

3.3-2 Irrigation period

How often should the farmer irrigate? The amount of water in the soil profile is consumed by the plant at a rate equal to the amount of evapotranspiration. The irrigation period or the time period between two consecutive irrigations is therefore

$$I_p = D_n/ET \qquad ---- (4)$$

where Ip is the irrigation period in days

ET is the average daily evapotranspiration in inches.

The shortest irrigation period is the critical one. The time per revolution of the center pivot system should not be longer than the critical irrigation period to insure that the crops' needs in the critical period are satisfied.

Example 2. Determine the critical irrigation period for the growing season of corn at Brookings, S.D. The net depth of application is 1.0 inch.

Month	May	June	July	August	September
ET, inches/day	0.06*	0.13	0.23	0.20	0.11
I_p, days	16	8	4**	5	9

* Result from Example 1.

** Critical irrigation period.

3.3-3 Annual time of operation

The annual time of operation is the amount of time when the system delivers water to the irrigated area. Crops in an irrigated area receive water from both irrigation and rainfall. The rainfall available for crop use is referred to as effective rainfall. Factors influencing rainfall effectiveness include the amount of rainfall, evapotranspiration, and the net depth of application (SCS, 1967).

Table 7 is prepared for estimating effective rainfall based upon the result published by Soil Conservation Service (1967).

The amount of evapotranspiration provided by irrigation is the annual irrigation requirement. The relationship between the annual irrigation requirement and the annual time of operation is defined as

$$T_o = IR\ (T_r)/D_n \qquad ----\ (5)$$

where T_o is the annual time of operation in hours,

IR is the annual irrigation requirement in inches,

T_r is the time per revolution of center pivot system in hours,

D_n is the net depth of application in inches.

The following example illustrates how to determine annual time of operation.

Example 3: Determine the annual time of operation for irrigating corn at Brookings, South Dakota.

Input information:

Growing season of corn is May 15 - September 15

Time per revolution is 3 days (72 hours)

Net depth of application is 1.0 inch

Line	Month	May	June	July	August	September
(1)	ET, inches	1.83*	3.76	7.06	6.20	3.36
(2)	Rainfall, inches	2.90	4.05	2.58	2.74	2.15
(3)	Effective rainfall inches (Table 7)	1.39	2.02	1.69	1.66	1.12
(4)	(1)-(3)	0.44	1.73	5.35	4.53	2.24
(5)	IR, inches	0.22**	1.73	5.35	4.53	1.12**

* Result from Example 1

** Use half the value in (4) to adjust for the growing season

Annual IR = 0.22 + 1.73 + 5.35 + 4.53 + 1.12 = 12.95 inches (Use 13 inches)

T_o = 13 (72)/1.0 = 936 hours. (Use 900 hours)

TABLE 7: AVERAGE MONTHLY EFFECTIVE RAINFALL* AS RELATED TO MEAN MONTHLY RAINFALL AND AVERAGE MONTHLY EVAPOTRANSPIRATION

MONTHLY MEAN RAINFALL inches	AVERAGE MONTHLY EVAPOTRANSPIRATION, inches 0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0
	AVERAGE EFFECTIVE RAINFALL, inches								
0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.22**	0.23	0.25	0.26	0.28	0.29	0.31	0.32	0.35
1.0	0.45	0.49	0.51	0.54	0.57	0.60	0.64	0.68	0.72
1.5	0.67	0.72	0.75	0.79	0.84	0.89	0.94	0.99	1.05
2.0	0.88	0.93	0.98	1.04	1.10	1.16	1.22	1.30	1.37
2.5		1.13	1.20	1.27	1.34	1.42	1.50	1.59	1.68
3.0		1.33	1.41	1.49	1.58	1.67	1.76	1.86	1.97
3.5		1.52	1.62	1.71	1.81	1.91	2.02	2.13	2.26
4.0		1.72	1.82	1.92	2.03	2.15	2.27	2.40	2.53
4.5			2.01	2.13	2.25	2.38	2.51	2.66	2.81
5.0			2.20	2.33	2.46	2.60	2.75	2.91	3.08
5.5			2.39	2.53	2.67	2.83	2.99	3.16	3.34
6.0			2.57	2.72	2.88	3.04	3.22	3.40	3.60
6.5			2.76	2.92	3.08	3.26	3.45	3.64	3.85
7.0				3.10	3.28	3.47	3.67	3.88	4.10
7.5				3.29	3.48	3.68	3.90	4.12	4.35
8.0				3.48	3.68	3.89	4.11	4.35	4.60

* Based on 1-inch net depth of application

** Values below line exceed monthly evapotranspiration and are to be used for interpolation only.

3.3-4 Time of Application

The last key question is how long should a specific point in the irrigated area be irrigated? In Figure 6, consider a point B located at the same distance as a sprinkler. Irrigation at B starts when the sprinkler is at A and ends when the sprinkler is at C. The arc distance of AC is very close to the range of coverage (wetted diameter) of the sprinkler. The time required for the sprinkler to travel from A to C, or the time of application at B, is approximately

$$T_a = S_c \, (T_r)/2\pi r \qquad ---- (6)$$

where T_a is the time of application in hours,

S_c is the wetted diameter of the sprinkler in feet,

T_r is the time per revolution in hours,

r is the radial distance of the sprinkler in feet.

Example 4: Determine the time of application for a point 1,285 feet from the pivot.

The gross depth of application is 1.25 inches and,

the time per revolution is 3 days (72 hours).

A sprinkler is located 1,285 feet from the pivot with a range of coverage of 90 feet.

$$T_a = 90\ (72)/2\ (3.14)\ 1285 = 0.80 \text{ hours}$$

4. Fluid Mechanics of Center Pivot Irrigation System

Transporting irrigation water requires energy for the engine to drive the pump. The study of the movement of water, the energy, and the rate of supplied energy is the field of fluid mechanics.

4.1 Discharge

Discharge is the rate at which water is being delivered to the irrigated area. Water, equivalent to the gross depth of application, is distributed to the irrigated area during the time per revolution, therefore

$$Q = 453 \cdot A \cdot D_G/T_r \qquad ---- (7)$$

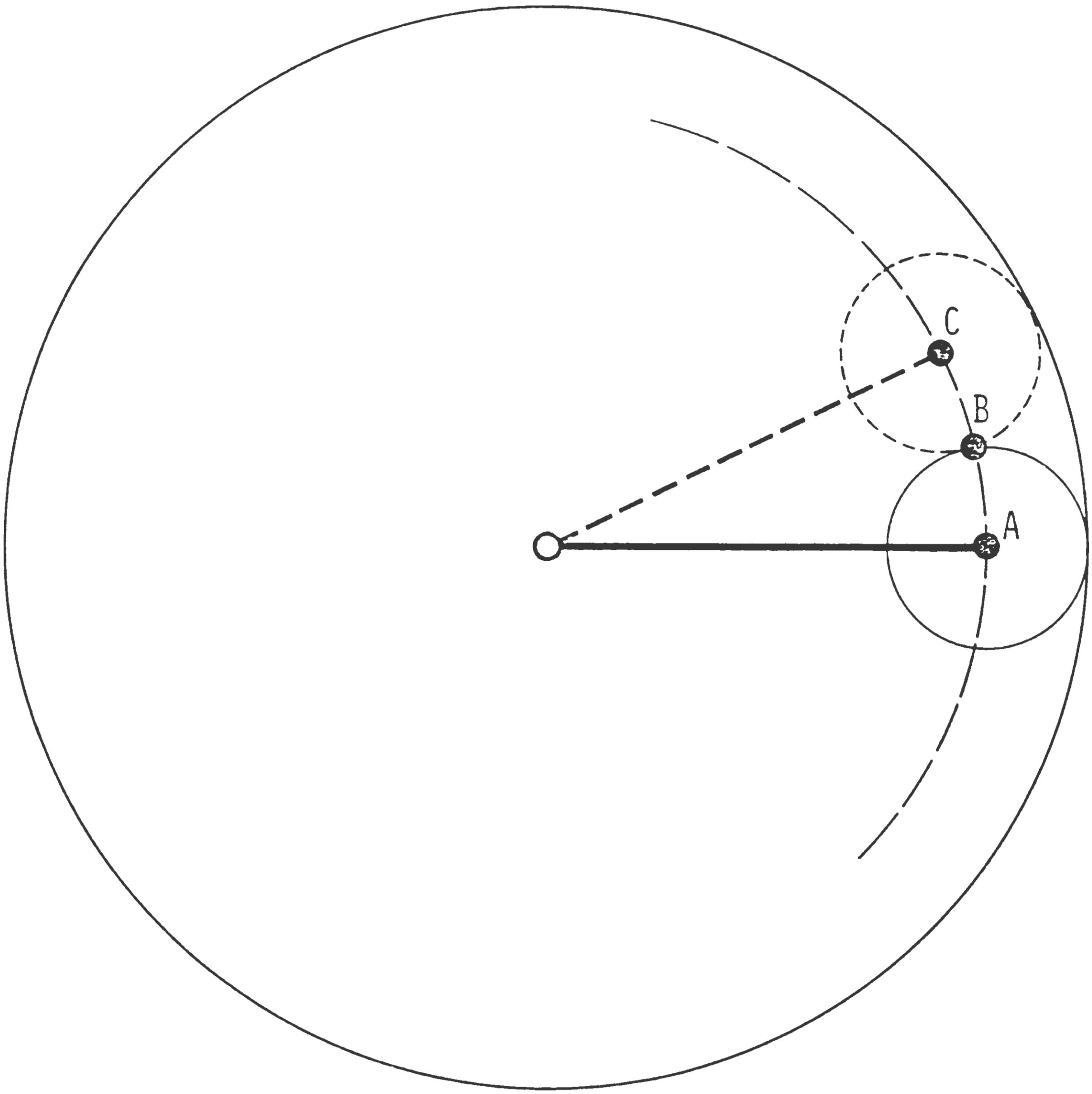


FIGURE 6: POSITIONS OF THE LATERAL AT THE START AND AT THE END OF WATER APPLICATION FOR A POINT NEAR THE BOUNDARY OF IRRIGATED AREA

where Q = the discharge in gallons per minute,

A = the acres irrigated,

D_G = the gross depth of application in inches,

T_r = the time per revolution in hours,

1 acre inch per hour = 453 gallons per minute.

Example 5: Determine the discharge of a center pivot system which distributes 1.25 inches (the gross depth of application) in 72 hours (the time per revolution) to an irrigated area circular in shape with a radius of 1320 feet.

$$A = \pi\ (1320)^2/43,560 = 125.7 \text{ acre}$$

where 1 acre = 43,560 square feet.

The discharge is by Equation 7

$$Q = 453\ (125.7)\ 1.25/72 = 989 \text{ gpm}$$

4.2 Lift

The work load involved in irrigation depends on the discharge of the center pivot system and the height the water has to be lifted. This height is the lift, and is classified into three types.

4.2-1 Elevation difference

The first type of lift is the elevation difference between the water source and the end sprinkler. When water is pumped from a well, the ground water will drop. This is the drawdown.

The amount of drawdown depends on the discharge and the water bearing formation surrounding the well. The relationship between the discharge and the drawdown is called the characteristics curve of a well. This should be determined by the well drilling company during the pumping test. An example of the characteristic curve is shown as follows:

Example 6: Characteristic curve of a well

Discharge in gpm	100	200	400	600	800	1000
Drawdown in feet	4	8	16	25	35	45

4.2-2 Pressure head

The second type of lift is associated with the pressure at the end sprinkler. Pressure is required to spread water to the surrounding area. If there is no pressure there is no sprinkler discharge.

Pressure is usually expressed in pounds per square inch. When the pressure is represented by feet of water, it is referred to as the pressure head. The pressure head is determined by

$$y = 2.31 \cdot P \qquad \text{- - - - (7)}$$

where y = the pressure head in feet,

P = the pressure in pounds per square inch,

1 pound per square inch = 2.31 feet of water.

Example 7: Determine the pressure head at the end sprinkler. The pressure at the end sprinkler is 50 pounds per square inch.

$$y = 2.31\ (50) = 115.5$$

4.2-3 Friction loss

The main part of this energy loss, the third type of lift, is due to friction losses. Friction loss in a pipe depends on diameter, discharge, length, and surface roughness. Scobey's formula is used to estimate this friction loss

$$h_f = K_s \cdot L \cdot Q^{1.9} \cdot D^{-4.9}\ (1.45 \times 10^{-8}) \qquad \text{- - - - (8)}$$

Where h_f = the friction loss in a supply line in feet,

K_s = the roughness coefficient of the pipe,

L = the length of pipe in feet,

Q = the discharge of pipe in gallons per minute,

D = the inside diameter of pipe in feet,

(approximately 98% of the outside diameter)

1.45×10^{-8} = the conversion constant of units.

A graphical representation of this equation (Figure 7) shows the friction loss in practice. The following example illustrates the procedure to determine friction loss of asupply line.

Example 8: Determine the friction loss in a supply line 1870 feet long, 8 inches in diameter (O.D.) with a discharge of 989 gpm and with a roughness coefficient of 0.34.

(1) Solution by formula:

$$h_f = 0.34\ (1870)\ 989^{1.9}\{(0.98)(8/12)\}^{-4.9}\ (1.45 \times 10^{-8})$$
$$= 36.4 \text{ ft}$$

(2) Solution by Figure 7:

$$h_f/100' = 1.97 \text{ feet}$$

$$h_f = 1.97\ (1870/100) = 36.8 \text{ feet}$$

The discharge in a lateral decreases down the pipe towards the end sprinkler because part of the discharge goes out through the sprinklers along the lateral. The friction loss, per unit length of lateral, decreases because of the decrease in pipe discharge.

The total friction loss in a lateral must be less than the loss in a corresponding supply line with the same total discharge, diameter, length, and roughness coefficient. It is possible to represent the friction loss in a lateral as a fraction of that in the corresponding supply line. This is referred to as the friction factor and is 0.543 (Chu, 1972). The friction loss in the lateral of a center pivot system is, therefore

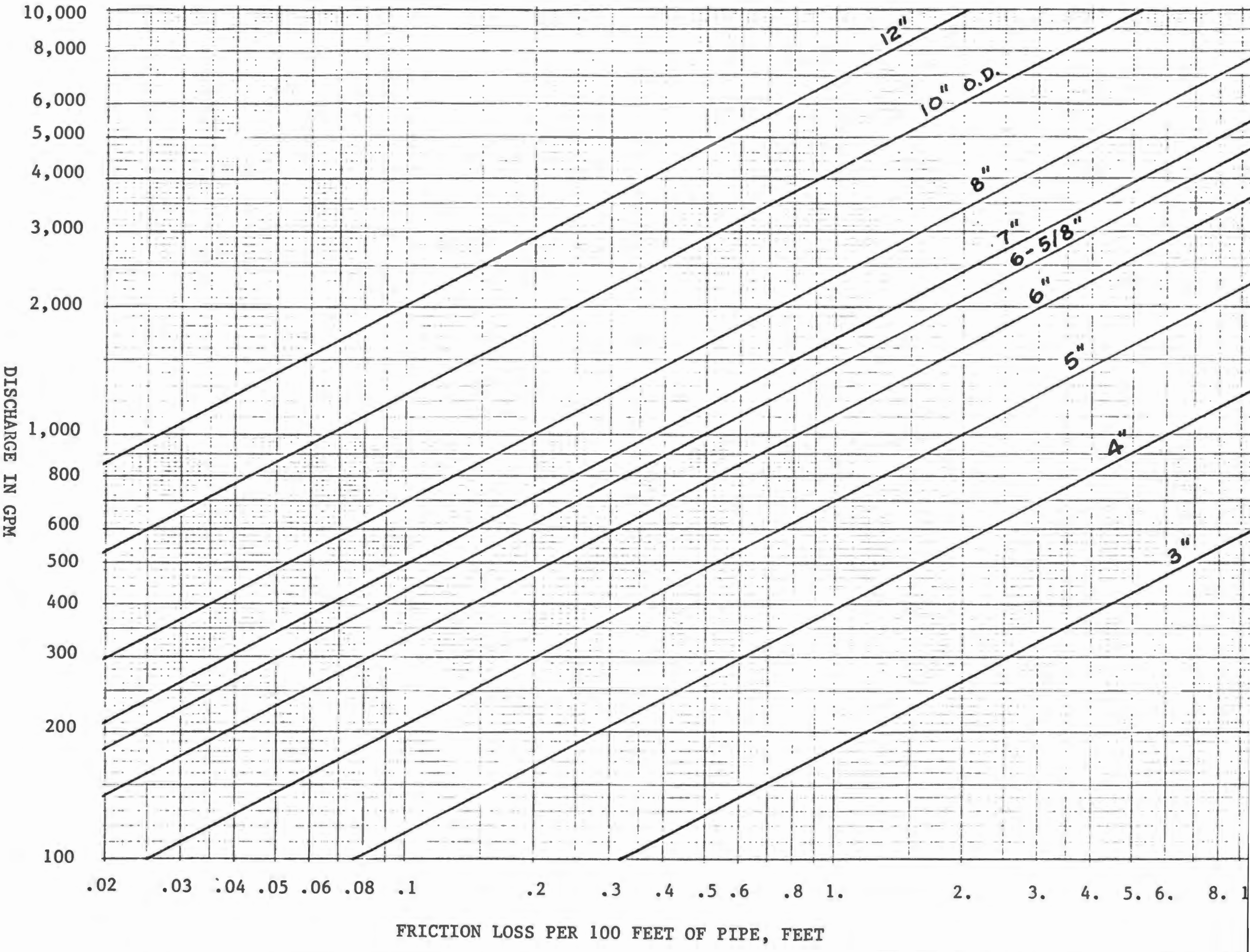
$$h_L = 0.543 \cdot h_f \qquad \text{- - - - (9)}$$

where h_L = the friction loss in the lateral, in feet,

h_f = the friction loss in the corresponding supply line, in feet.

Example 9: Determine the friction loss in the lateral of a center pivot system with a discharge of 989 gpm, a length of 1290 and a diameter of 6-5/8 inches and a roughness coefficient of 0.34

Solution: The friction loss of the corresponding supply line is from Figure 7.


12"
10" O.D.
8"
7"
6-5/8"
6"
5"
4"
3"
10,000
8,000
6,000
5,000
4,000
3,000
2,000
1,000
800
600
500
400
300
200
100
DISCHARGE IN GPM
.02
.03
.04
.05
.06
.08
.1
.2
.3
.4
.5
.6
.8
1.
2.
3.
4.
5.
6.
8.
FRICTION LOSS PER 100 FEET OF PIPE, FEET

$$h_f/100 \text{ ft} = 4.9 \text{ ft}$$

$$h_f = 4.9\ (1290/100) = 63.2 \text{ ft}$$

The friction loss of the lateral is by Equation (9)

$$h_L = 0.543\ (63.2) = 34.3 \text{ ft}$$

4.3 Energy equation and total lift

Energy expressed in feet of water is the lift. The energy equation can be used to describe the relationship between the lift of two different points in a center pivot

$$(E_1 + Y_1) - (E_2 + Y_2) = h_{1,2} \qquad ---- (10)$$

where E_1, E_2 = the elevation at point 1 and point 2, in feet,

Y_1, Y_2 = the pressure head at point 1 and point 2, in feet,

$h_{1,2}$ = the energy loss between points 1 and 2, in feet.

Let point 1 be the water source and point 2 be the end gun. The energy equation becomes

$$H = (E_g - E_s) + Y_g + h_f + h_L \qquad ---- (11)$$

where H = the pressure head required at the water source, in feet,

E_g, E_s = the elevation at the end gun and at the water source respectively, in feet,

Y_g = the pressure head required at the end gun, in feet,

h_f, h_L = the friction loss in the supply line and in the lateral respectively, in feet.

The water source pressure head is referred to as the total lift. This lift has to be provided by the pump.

Example 10: Determine the total lift of a center pivot system

Input information: Elevation at the end gun = 1642 ft.

Elevation at the pump = 1622 ft.

The static water table is 10 ft below the motor.

The discharge of the pump = 989 gpm (from Example 5).

The characteristic curve of the well is represented by Example 6.

The pressure required at the end gun = 50 psi (from Example 7).

The friction loss in the supply line is 36.8 ft (from Example 8) and

the friction loss in the lateral is 34.3 ft (from Example 9.)

Solution:

(1) From Example 6 the drawdown is interpolated to be 44 ft. So the water source elevation when the system is under operation is

$$1622 - 10 - 44 = 1568 \text{ ft}$$

(2) The pressure head at the end gun is by Equation (7) or from Example 7 is

$$2.31\ (50) = 115.5 \text{ ft}$$

(3) The total lift is by Equation (11)

$$H = (1642 - 1568) + 115.5 + 36.8 + 34.3 = 260.6 \text{ ft}$$

The energy equation can be used to check pressure at various points along the pipeline. Let point 1 be a certain point and point 2 the end sprinkler. The energy equation becomes

$$Y_1 = (E_g - E_1) + Y_g + h_{1,g} \qquad \text{- - - - (12)}$$

where Y_1 = the pressure head at the point of interest, in feet,

E_1 = the elevation at the point of interest, in feet,

$h_{1,g}$ = the energy loss between point 1 and the end gun, in feet.

The following example shows the procedure to check the pressure.

Example 11: Check the pressure at the pivot point.

Input information: Elevation at the pivot point = 1647 ft. All the other information is the same as that give in Example 10.

Solution: The elevation at the pivot point is higher than that of the end gun, so the pressure at the pivot point should be checked. From Equation (12)

$$Y_1 = (1642 - 1647) + 115.5 + 34.3 = 144.8 \text{ ft}$$

The pressure at the pivot point is figured by equation 7

$$P_1 = 144.8/2.31 = 62.7 \text{ psi}$$

In this case the pressure is considered to be adequate. If the pressure at any point is considered not acceptable then the total lift should be increased to fulfill the requirement.

4.4 Pump and Motor

The energy loss of the pump and that of the electric motor are not considered as part of the third type of lift. The pump efficiency and the motor or engine efficiency take these energy losses into account. The relationship between the lift and the discharge is referred to as the performance curve of a pump.

An example is shown in figure 8. Proper combination of lift and discharge results in high pump efficiency. Pump discharge and system discharge must be matched to insure efficient performance. Frequently, one pump stage is not enough to produce the total lift required by the irrigation system. A pump with multiple stages is needed to fulfill the demand.

The power required by the irrigation system is defined as

$$W_w = Q \cdot H/3960 \qquad \text{- - - - (13)}$$

where W_w = the power required by the system, in horsepower,

Q = the discharge, in gpm,

H = the total lift, in feet,

1 horsepower = 3960 gpm - feet.

The power of a pump is determined by

$$W_p = W_w/e_p \qquad \text{- - - - (14)}$$

where W_p = the power of a pump, in horsepower,

e_p = the pump efficiency.

In a similar manner, the power to a motor is

$$W_m = 0.746\ W_p/e_m \qquad \text{- - - - (15)}$$

where W_m = the power to a motor (or engine) in kilowatts,

e_m = the motor (or engine) efficiency,

1 horsepower = 0.746 kilowatts

Example 12: Select a pump and determine the power of the pump and the electric motor.

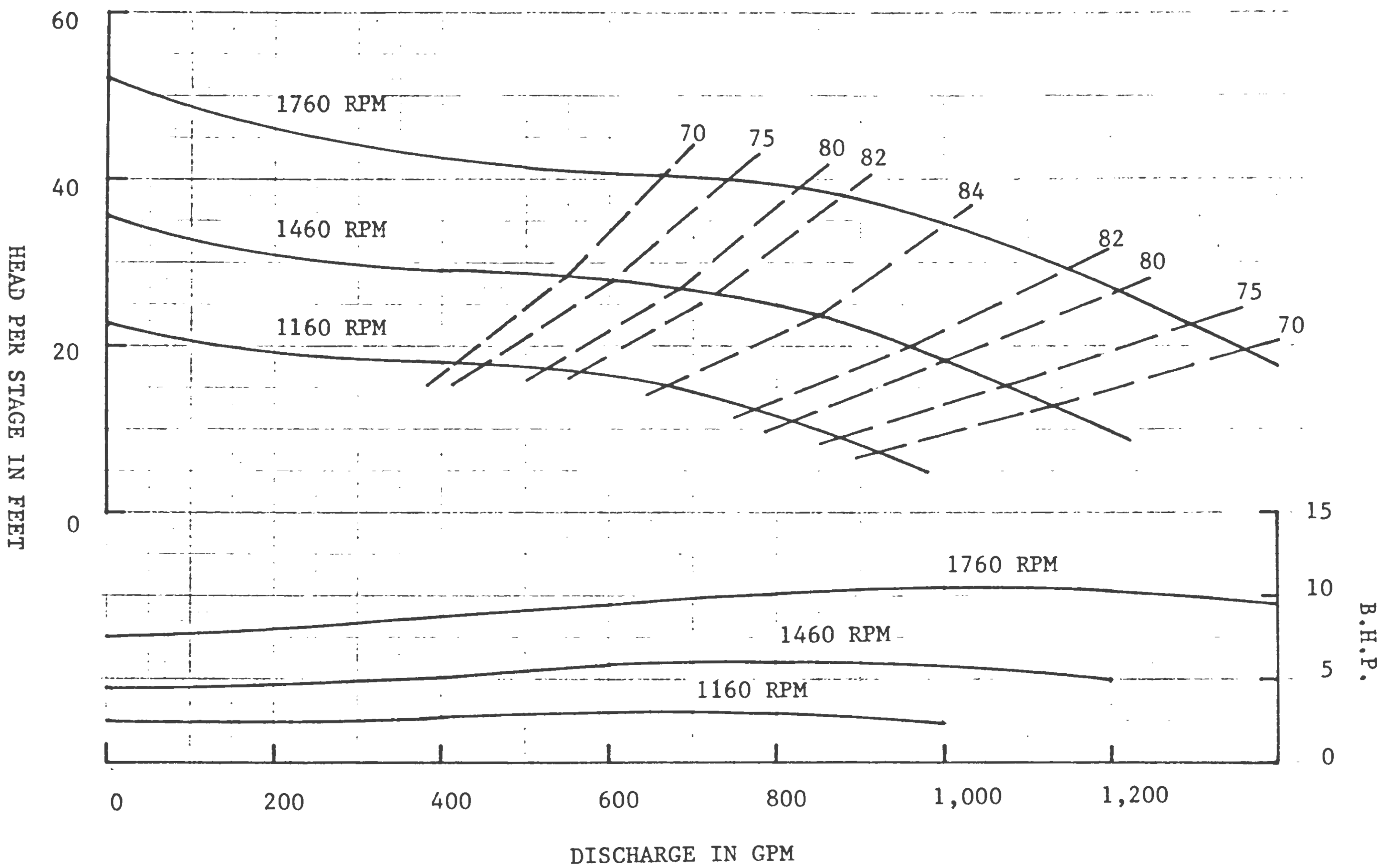


FIGURE 8: PERFORMANCE CURVE OF A PUMP

Input information: The discharge = 989 gpm (from Example 5).
The total lift = 260.6 ft (from Example 10 and
the motor efficiency = 0.9.

Solution: The pump efficiencies for various pumping conditions shown in Figure 8 at a discharge of 989 gpm are:

Pumping condition	Efficiency
1760 rpm	0.84
1460 rpm	0.80
1160 rpm	0.60

The pump operated at 1760 rpm is selected because of its efficient performance. The lift provided by one stage is 35 feet so

Number of stages = 260.6/35 = 7.45 (Use 8 stages)

From Equation (13), the power required by the system is

$$W_w = 989\ (260.6)/3960 = 65.1\ \text{h.p.}$$

The power of the pump and that of the motor by Equations (14) and (15) are

$$W_p = 65.1/0,84 = 77.5\ \text{h.p.}$$

$$W_m = 0.746\ (77.5)/0.9 = 64.2\ \text{kw}$$

4.5 Pressure Distribution in the Lateral

Sprinkler discharge depends on the operating pressure. Proper selection of sprinklers requires information on the sprinkler pressure. The pressure in the lateral varies from the pressure at end sprinkler P_g to the pressure at the pivot P_p. Based upon the energy equation and assuming the elevation difference is negligible, we have

$$P_p - P_g = H_L/2.31 \qquad \text{- - - - (16)}$$

P_g = the pressure at the end sprinkler in psi,

H_L = the friction loss in the lateral, in feet.

The pressure distribution in a lateral can be determined with the use of the distribution factor (Chu, 1972). The distribution factor is a function of the distance ratio r/R where r is the radial distance of the sprinkler from the pivot and R is the wetted radius of the irrigated area. The graphical representation of the distribution factor is shown in Figure 9. The sprinkler pressure is determined by

$$P_r = P_g + (P_p - P_g) \cdot D_F \qquad \text{- - - - (17)}$$

where P_r = the sprinkler pressure in psi,

P_g = the end sprinkler pressure in psi,

P_p = the pivot pressure in psi,

D_F = the distribution factor

Example 13: Determine the sprinkler pressure with radial distance of 0 ft, 330 ft, 660 ft, 990 ft, and 1290 ft from the pivot.

Input information: The end sprinkler pressure = 50 psi. The friction loss in the lateral = 34.3 ft (from Example 9) and the wetted radius of the irrigated area is 1320 ft.

Solution:

(1) The pressure difference $P_p - P_g$ is by Equation (16)

$$P_p - P_g = 34.3/2.31 = 14.9 \text{ psi}$$

(2) The pressure distribution at the sprinklers is by Equation (17)

Radial Distance r, feet	r/R	Distribution factor D_F (Figure 9)	Pressure difference P_r-P_g, psi	Pressure at Sprinklers P_r, psi
0	0	1.000	14.9*	64.9
330	.250	.555	8.3	58.3
660	.500	.215	3.2	53.2**
990	.750	.030	0.5	50.5
1290	.977	0	0	50.0

* From Equation (16) $P_p - P_g = 14.9$

** From Equation (17) $P_r = 50 + 14.9\ (0.215) = 53.2$ psi

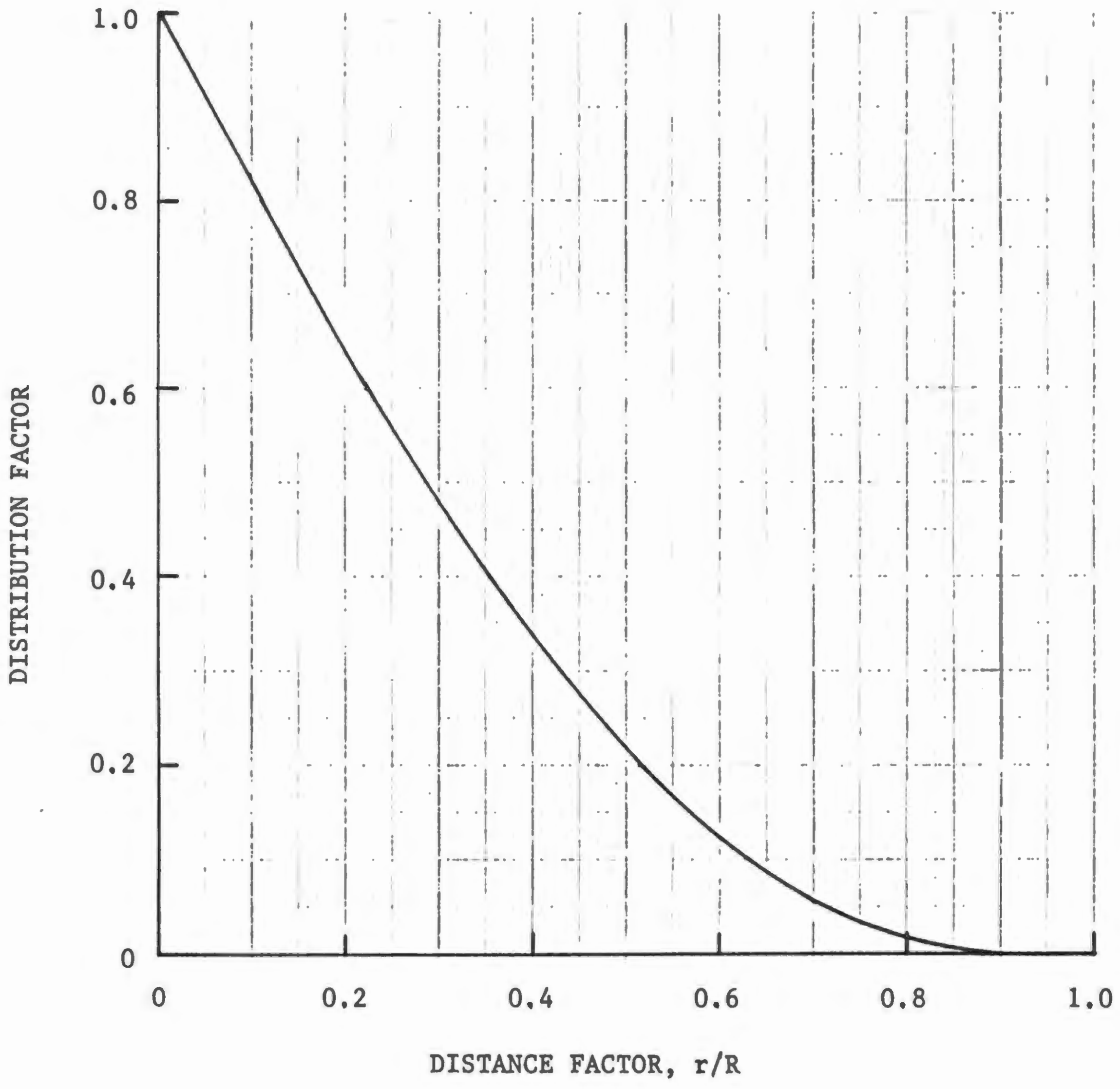


FIGURE 9: DISTRIBUTION FACTOR OF A CENTER PIVOT SYSTEM

The pressure distribution represents the result on a level surface. In practice, it changes when there is elevation differences. However, if the maximum elevation difference from the end sprinkler along the lateral is within 10% of the pressure head at the end sprinkler (ASAE Minimum Performance for Sprinkler Systems), then the result described by Equation (17) is still considered as acceptable. Pressure head should be adjusted to the elevation difference based upon the relationship described by the energy equation (equation 12) that

$$P_r = (E_g - E_1)/2.31 + P_{level} \qquad \text{- - - - (18)}$$

where P_r = the pressure at the sprinkler in psi,

$E_g - E_1$ = the elevation difference from the end sprinkler, in feet,

P_{level} = the pressure at the sprinkler on a level surface determined by Example 13.

Example 14: Determine the pressure head at the sprinklers when the elevation at the sprinklers are given as follows:

Radial distance, ft.	0	330	660	990	1290
Elevation, ft	1647*	1643	1632	1637	1642*

* From Examples 10 and 11 respectively -

Other information remains the same as Example 13.

Solution: The maximum elevation difference is 1642 - 1632 = 10 ft.

The pressure at the end gun is 50 psi (example 13) = 115.5 ft.

The allowable difference in elevation is 10% (115.5) = 11.6 ft (>10 ft), so the elevation difference is acceptable. The pressure distribution is:

Radial distance r, feet	Elevation E_1, feet	P_{level} in psi from Ex. 13	Pressure at sprinkler P_r, psi
0	1647	64.9	62.7*
330	1643	58.3	57.9
660	1632	53.2	57.5
990	1637	50.5	52.7
1290	1642 (E_g)	50.0	50.0

* From Equation (18) $P_r = (1642-1647)/2.31 + 64.9 = 62.7$ psi

5. Center Pivot Irrigation System Design

The previous sections present basic knowledge concerning center pivot irrigation. This section describes the application of this basic knowledge.

5.1 Test the Application Rate

To test the application rate of a center pivot system, the designer should first estimate the surface pondage under an elliptical water application pattern (figure 4). Next, he estimates the surface retention capacity under a constant water application pattern (figure 5). If the surface pondage is less than or equal to the surface retention capacity, then runoff will not occur and the application rate of the system is not excessive.

The critical runoff area is near the outer boundary of the irrigated area. This is because the application rate is high (Dillon et al. 1972). A thin strip of land along the outer boundary of the sprinkler may be taken as a sample from the critical area for analysis. If surface runoff does not occur on this strip, then the application rate of the center pivot system is acceptable.

The relationship between the gross depth of application and the maximum application rate under an elliptical pattern is needed for the calculations of the application rate testing. This relationship is given by Dillon et al. (1972) as

$$h = (4/\pi)\, D_G/T_a \qquad \text{- - - - (19)}$$

where h = the maximum application rate of an elliptical pattern in inches per hour,

D_g = the gross depth of application in inches,

T_a = the time of application, in hours.

An example is prepared to illustrate the testing procedure.

Example 15: Test the feasibility of the application rate of a center pivot system.

Input information: The net application rate is selected to be 1.0 inch. The gross depth of application is estimated to be 1.25 in. The radial distance from the last sprinkler to the pivot is 1,285 ft. The sprinkler coverage of a large sprinkler (for constant spacing system) is 175 feet and that of a medium sprinkler (for variable spacing system) is 90 ft. The time per revolution is 72 hours. The soil parameter for a 0.5 intake family soil is K = 0.40 iph and SM = 1.55 inches (Table 5). The crop is corn (row crop) and the average ground slope is 3%.

Calculations:

(1) Determine the surface pondage for a variable spacing system.
The time of application, referring to Example 4, is 0.80 hours.

The maximum application rate is by Equation (19)

$$h = (4/\pi)\ 1.25/0.80 = 1.99 \text{ iph}$$

The values of the parameters are

$$K/h = 0.40/1.99 = 0.20$$

and

$$D_G/SM = 1.25/1.55 = 0.81$$

Enter the two parametric values in Figure 4 to obtain the surface pondage to be

$$S_p/D_G = 0.15$$

$$S_p = 0.17\ D_G = 0.17\ (1.25) = 0.21 \text{ inches}$$

(2) Determine the surface retention capacity

The allowable rate for row crops on a 0.5 intake family soil with 3% slope is estimated to be (Table 6)

$$I = 2.00 \times 2/3 = 1.33 \text{ iph}$$

The value of the parameter

$$K/I = 0.40/1.33 = 0.30$$

Enter the parametric values of D_G/SM and K/I into figure 5 to obtain the surface retention capacity, D_c, as

$$D_c/D_G = 0.065$$

$$D_c = 0.065\ (1.25) = 0.08 \text{ in}$$

The surface pondage is larger than the retention capacity, so runoff will occur. The application rate under variable spacing is excessive. An alternative is to use a constant spacing system.

(3) Determine the surface pondage under a constant spacing system. The time of application for a sprinkler coverage of 175 ft is

$$T_a = 175\ (72)/(2 \cdot \pi \cdot 1285) = 1.56 \text{ hours}$$

and

$$h = (4/\pi)\ 1.25/1.56 = 1.02 \text{ iph}$$

The value of the parameter

$$K/h = 0.40/1.02 = 0.39$$

The value of D_G/SM is 0.81. Enter the two parametric values into Figure 4 to find $S_p/D_G = 0$

There is no surface pondage under a constant spacing system. All water infiltrates into the ground and application rate is acceptable.

5.2 Select the supply line size

Suppose a designer selected a rather large pipe size for the supply line. Based upon the information on discharge, roughness coefficient, length, and size of pipe now at his disposal, he calculated the friction loss for the selected supply line. Next he replaced the pipe size with a smaller one. Such a replacement brought about two changes. First, the pipe cost is reduced because the new pipe is smaller in size. Second, the energy cost will increase because the friction loss of the smaller pipe is higher than that of the larger pipe. If the saving in pipe cost surpasses the increase in energy cost, such a change in pipe size is feasible. He could repeat this process to obtain further cost reductions. When the saving in pipe cost becomes less than or equal to the increase in energy cost then the optimum pipe size is obtained.

The previous statements can be described as follows:

$$\text{Pipe cost saving} = (C_{pb} - C_{ps}) \cdot CRF \qquad ---- (20)$$

where C_{pb} = the pipe cost per unit length for the large pipe in \$/ft,

C_{ps} = the pipe cost per unit length for the small pipe in \$/ft,

CRF = the capital recovery factor.

$$\text{energy cost increase} = 0.000188\,(h_{fs} - h_{fb}) \cdot C_{KH} \cdot Q \cdot T_o/E_p \cdot E_m \qquad ---- (21)$$

where h_{fs} = the friction loss per unit length of the small pipe in feet,

h_{fb} = the friction loss per unit length of the large pipe in feet,

C_{KH} = the energy cost per kilowatt hour of energy in \$/KWH,

Q = the discharge in gpm,

T_o = the annual time of operation in hours,

E_p = the pump efficiency

E_m = the motor (or engine) efficiency,

1 KWH = 0.000188 feet-gpm-hour

The criterion to obtain optimum pipe size is

$$\text{pipe cost saving} \leq \text{energy cost increase}$$

or

$$(C_{pb} - C_{ps}) \cdot CRF \leq 0.000188\,(h_{fs} - h_{fb}) \cdot C_{KH} \cdot Q \cdot T_o/E_p \cdot E_m \qquad ---(22)$$

A graph representing the relationship between the quantity $h_{fs} - h_{fb}$ and the discharge Q is prepared in Figure 10 to speed the calculations involved. The procedure of pipe size selection is described in the following example.

Example 16: Determine the optimum pipe size of the supply line.

Input information: The discharge = 989 gpm (from Example 5).

The annual time of operation = 900 hours (from Example 3).

The pump efficiency = 0.84 (from Example 12).

The motor efficiency = 0.9.

The energy cost = \$0.025/KWH (1976 estimate).

The capital recovery factor = 0.117 and the pipe cost of steel pipe (1976 estimate).

Pipe size	5"	6"	7"	8"	10"	12"
Pipe cost, \$/ft	3.00	3.50	4.00	4.60	5.90	7.60

Solution: Let the quantity $0.000188 \cdot C_{KH} \cdot Q \cdot T_o/E_p \cdot E_m$ be represented by a constant K and for this example

$$K = 0.000188\ (0.025)\ 989\ (900)/0.84\ (0.90) = \$5.53$$

Substitute K in equation (21) to obtain

$$\text{energy cost increase} = K\ (h_{fs} - h_{fb}) \quad \text{--- (23)}$$

Pipe Size in inches	Pipe Cost C_p	Cost difference $C_{pb}-C_{ps}$	Saving/ft (Eq. 20)	$h_{fs}-h_{fb}$ (Figure 10)	Cost increase/ft (Eq. 23)
12	7.60				
		1.70	\$0.20	0.0039	\$0.02
10	5.90				
		1.30	\$0.15	0.0129	\$0.07
8	4.60				
		0.60	\$0.07***	0.0182	\$0.10
7	4.00				
		0.50	\$0.06	0.0421	\$0.23
6	3.50				
		0.50	\$0.06*	0.1170	\$0.65**
5	3.00				

* pipe cost saving = 0.50 x CRF = 0.50 x 0.117 = \$0.06/ft

** energy cost increase = 0.1170 x K = 0.1170 x 5.53 = \$0.65/ft

*** select 8 inches because when 8 inches is replaced by 7 inches the pipe cost savings = \$0.07 $\leq$ the energy cost increase = \$0.10

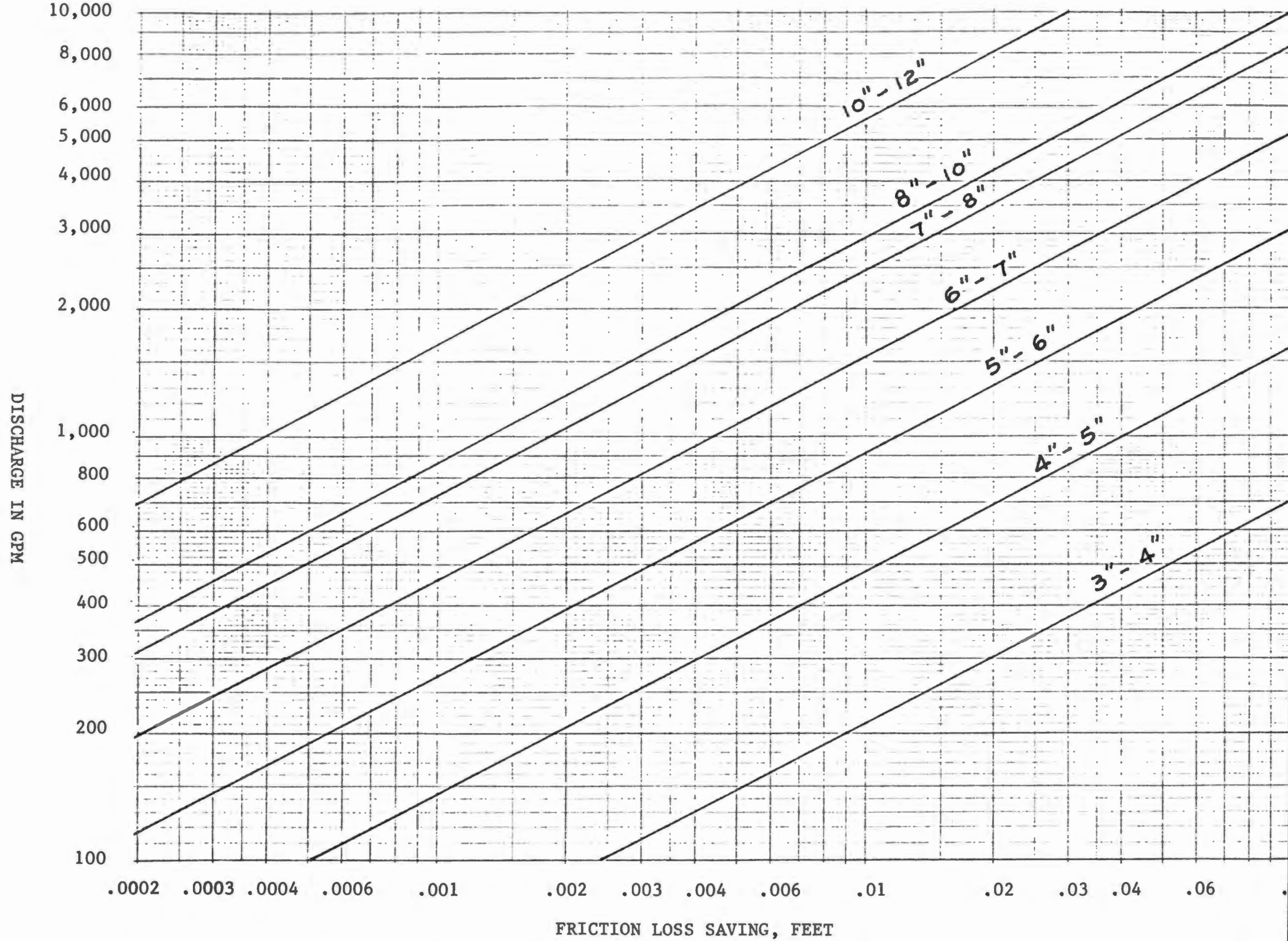


FIGURE 10: FRICTION LOSS SAVING AND DISCHARGE (BASED ON SCOBEY'S ROUGHNESS COEFFICIENT OF 0.34)

5.3 Select the lateral size

The size of the lateral can be determined by the same procedure described in the previous section, except the friction factor of a center pivot system (equation 9) should be included in a constant K_L where

$$K_L = 0.543\ K \qquad ---- (24)$$

and

$$\text{energy cost increase for a lateral} = K_L\ (h_{fs} - h_{fb}) \qquad ---- (25)$$

Example 17: Determine the lateral size of a center pivot system.

All the input information is the same as that in Example 16.

Pipe Size in inches	Saving/ft (example 16)	Cost increase/ft (from example 16)	Cost increase of lateral/ft
10			
	$0.15	$0.07	$0.04
8			
	$0.07	$0.10	$0.05
7			
	$0.06**	$0.23	$0.12
6			
	$0.06	$0.65	$0.35*
5			

* energy cost increase for a lateral = 0.543 (0.65) = $0.35

** select 7 inches because when 7 inches is replaced by 6 inches the pipe cost saving = $0.06 < the energy cost increase = $0.12

In practice, lateral size selection is more complicated than what is described here. When lateral size is reduced, the load on the towers is also reduced, so there is additional saving on the cost of the towers. When the saving on the towers is added on to the saving of pipe cost, the optimum pipe size will reduce also. This is why the lateral size on a regular center pivot system in practice ranges from 6 inches to 6-5/8 inches instead of the 7 inches determined in this section.

5.4 Select Sprinklers for a Constant Spacing System

Sprinkler spacing on a center pivot system is the basic input information. The objective is to select the right set of sprinklers for the lateral. Consider a sprinkler with a constant sprinkler spacing of S_s and a radial distance r from the pivot. The irrigated area attributed to this sprinkler is

$$a = 2\pi \cdot r \cdot S_s/43560$$

where a = the irrigated area of the sprinkler in acres

r = the radial distance from the pivot in feet

S_s = the constant sprinkler spacing, in feet

1 acre = 43560 square feet

Equation (26) represents a ring shaped area bounded by two concentric circles with radii $r \pm S_s$. Some water is distributed outside the bounds set by the two circles. Apparently the area specified by Equation (26) is conservative. However, there is also an approximately equal amount of water from other sprinklers carried inside the ring shaped area. The tradeoff is nearly equal. This is why Equation (26) is an acceptable representation of the irrigated area of a sprinkler.

It follows from Equation (7) that the required sprinkler discharge is

$$q = 453(2\pi \cdot r \cdot S_s/43560) \cdot D_G/T_r \qquad ---- (27)$$

where q = the required sprinkler discharge in gpm

D_G = the gross depth of application in inches

T_r = the time per revolution, in hours

Similarily the system discharge is represented by

$$Q = 453\ (\pi \cdot R^2/43560) \cdot D_G/T_r \qquad ---- (28)$$

where Q = the system discharge in gpm

R = the wetted radius of the irrigated area covered by the center pivot system, in feet.

Divide Equation (27) by (28) to obtain

$$q = 2 \cdot Q \cdot r \cdot S_s/R^2 \qquad ---- (29)$$

The design procedure in selecting sprinklers in summarized as follows:

1. Calculate the pressure difference between the end gun and the pivot.
2. Determine the pressure distribution in the lateral.
3. Calculate sprinkler discharge by Equation (29).

Example 18: Select sprinklers for a constant spacing system.

Input information:

The wetted radius of irrigation area, R = 1,320 ft (from Example 5).

The system discharge, Q = 989 gpm (from Example 5).

The constant sprinkler spacing is selected to be S_s = 30 ft.

The radial distance of the end gun, L = 1,290 ft.

The size of lateral is selected to be D = 7 inches and,

the operating pressure of the end gun is selected to be 70 psi (for large sprinklers on a constant spacing system).

Calculations:

(1) Determine the pressure difference or the friction loss.

Enter the values of Q = 989 gpm and D = 7 inches into figure 7 to obtain

$$H_f/100 \text{ ft} = 3.7 \text{ ft}$$

$$H_f = 3.7\ (1290/100) = 47.7 \text{ ft}$$

From Equation (9)

$$H_l = 0.543 \cdot H_f = 0.543\ (47.7) = 25.9 \text{ ft}$$

From Equation (16) the pressure difference is

$$P_p - P_g = 25.9/2.31 = 11.2 \text{ psi}$$

(2) Pressure distribution and sprinkler discharge

Radial distance r	Distance factor r/R	Distribution factor D_F from Fig. 9	Pressure distribution P_r, psi from Eq. 17	Sprinkler discharge q
1290	0.977*	0	70.0	43.9***
1260				42.9
1230				41.9
1200				40.9
1170				39.8
1140				38.8
1110				37.8
1080	0.818	0.012	70.1**	36.8
1050				35.8
1020				34.7
990				33.7
960				32.7
930				31.7
900				30.7
870	0.659	0.080	70.9	29.6
840				28.6
810				27.6
780				26.6
750				25.5
720				24.5
690				23.5
660	0.500	0.215	72.4	22.5
630				21.5
600				20.4
570				19.4
540				18.4
510				17.4
480				16.3
450	0.341	0.418	74.7	15.3
420				14.3
390				13.3
360				12.3
330				11.2
300				10.2
270				9.2
240	0.182	0.670	77.6	8.2
210				7.2
180				6.1
150				5.1
120				4.1
90				3.1
60				2.0
30	0.023	0.960	80.9	1.0

*$r/R = 1290/1320 = 0.977$

**$P_r = P_g + (P_p - P_g) \cdot D_F = 70 + (11.2)\ 0.012 = 70.1$ psi

***$q = 2\ (909)\ 1290\ (30)/1320^2 = 43.9$ gpm

(3) Sprinkler selection

Radial distance r feet	Pressure P_r, psi	Calculated sprinkler discharge gpm	Sprinkler from catalogue	Catalog sprinkler discharge gpm
1290	70.0	43.9	85-E-TNT-3/8"x7/32"-20^o	44.9
1260	"	42.9	70-E-TNT-3/8"x7/32"	42.2
1230	"	41.9	"	42.2
1200	"	40.9	80-E-TNT-11/32"x7/32"	40.1
1170	"	39.8	70-E-TNT-11/32"x7/32"	38.6
1140	"	38.8	"	38.6
1110	"	37.8	"	38.6
1080	"	36.8	"	38.6
1050	"	35.8	70-E-TNT-5/16"x7/32"	34.5
1020	"	34.7	"	34.5
990	"	33.7	"	34.5
960	"	32.7	70-EW-TNT-3/8"	33.2
930	"	31.7	70-E-TNT-9/32"x7/32"	30.4
900	"	30.7	"	30.4
870	"	29.6	"	30.4
840	"	28.6	70-EW-TNT-11/32"	28.5
810	"	27.6	"	28.5
780	"	26.6	70-E-TNT-9/32"x3/16"	27.4
750	"	25.5	70-EW-TNT-5/16"	23.9
720	"	24.5	"	23.9
690	"	23.5	"	23.9
660	"	22.5	70-E-TNT-1/4"x11/64"	22.6
630	"	21.5	"	22.6
600	"	20.4	70-E-TNT-7/32"x11/64"	19.0
570	75.0*	19.4	"	19.7
540	"	18.4	14070-TNT-15/64"x1/8"	17.8
510	"	17.4	"	17.8
480	"	16.3	14070-TNT-7/32"x1/8"	15.9
450	"	15.3	"	15.9
420	"	14.3	14070-TNT-13/64"x1/8"	14.5
390	"	13.3	14070-W-15/64"	13.6
360	"	12.3	14070-3/16"x1/8"-20^o	12.8
330	"	11.2	14070W-TNT-15/64"	10.2
300	"	10.2	"	10.2
270	"	9.2	14070-TNT-11/64"x3/32"	9.6
240	80.0*	8.2	14070-TNT-5.32"x3.32"	8.7
210	"	7.2	30-EW-TNT-5.32"	6.3
180	"	6.1	"	6.3
150	"	5.1	30W-TNT-9/64"	5.2
120	"	4.1	29B-TNT-1/8"	4.1
90	"	3.1	20C-TNT-7/64"	3.2
60	"	2.0	"	3.2
30	"	1.0	-	0
		Sum = 966.5		Sum = 967.0

* Pressure values rounded off to the nearest 5 psi's.

** Sum of sprinkler discharges.

(4) Additional sprinkler

The sum of the sprinkler discharges listed in part (3) does not check with the system discharge of 989 gpm. The reason is that the lateral is 1,290 ft long and the irrigated area assigned to the end gun is a 15 ft wide ring (the constant sprinkler spacing) on each side along its path of travel. But the total irrigated area extends to a radial distance of 1,320 ft, so there is a 15 ft wide ring of land along the periphery not included in the calculations. The discharge required by this outside strip is figured by Equation (29)

$$q = 2\ (989)(1320 - 15/2)\ 15/1320^2 = 22.4 \text{ gpm}$$

From the catalog (Rain Bird, 1978) the sprinkler 70 E-TNT-1/4 inch x 11/64 inches can deliver this amount of water (catalog sprinkler discharge is 22.6 gpm) at a pressure of 70 psi. However, the sprinkler can not be set at a radial distance of 1,312.5 ft because the lateral ends at 1,290 ft. So the next best thing is to set the sprinkler somewhere near the end gun, for example, at a radial distance of 1,285 ft. The total sprinkler discharge after this adjustment becomes 967.0 + 22.6 = 989.6 gpm, which checks favorably with the system discharge of 989 gpm.

5.5 Select spacings for a variable spacing system

The purpose of the variable spacing system is to arrange the sprinklers at strategic locations on the lateral so that the distribution of water along the lateral is uniform. Selecting the sprinkler type and size is the first step. Next, determine the pressure distribution by the procedure described in the previous section. The sprinkler discharges are obtained for various pressures specified by the pressure distribution. The objective is now to find the relationship between the spacing and sprinkler discharges so that the former quantity can be determined based upon the given information on the sprinkler discharges.

Consider the irrigated area between two adjacent sprinklers

$$a_b = \pi\ (r_d^{\ 2} - r_u^{\ 2})/43560 \qquad ---- (30)$$

where a_b = the irrigated area between two adjacent sprinklers in acres,

r_d = the radial distance of the downstream sprinkler from the pivot, in feet,

r_u = the radial distance of the upstream sprinkler from the pivot, in feet.

The discharge associated to this area should be the average discharge of the two sprinklers. Based upon Equation (7)

$$(q_u + q_d)/2 = 453\ \pi\ (r_d^{\ 2} - r_u^{\ 2}) \cdot D_G/43560\ T_r \qquad ---- (31)$$

where q_u = the upstream sprinkler discharge, in gpm,

q_d = the downstream sprinkler discharge, in gpm.

Combine Equations (28) and (31) to obtain

$$r_d^{\ 2} = r_u^{\ 2} + (q_u + q_d) \cdot R^2/2Q \qquad ---- (32)$$

The variable spacing is represented by

$$S_s = r_d - r_u \qquad ---- (33)$$

where S_s = the variable spacing in feet.

The procedure of selecting variable spacing is summarized as follows:

(1) Select the sprinkler and the pressure at the end gun.

(2) Determine the pressure distribution.

(3) Find the sprinkler discharge for various pressures specified by the pressure distribution.

(4) Start from the pivot where $q_u = 0$ and $r_u = 0$. So Equations (32) and (33) becomes

$$r_d^{\ 2} = q_d \cdot R^2/2Q = S_s^{\ 2} \qquad ---- (34)$$

(5) Equation (34) can be used to determine the radial distance of the first sprinkler.

(6) For the second sprinkler the value of r_d for the first sprinkler becomes the value of r_u. Equation (32) can be used to determine the radial distance of the second sprinkler and repeat this process.

Example 19: Select the sprinkler spacings for a variable spacing system

Input information:

The wetted radius of irrigated area = 1,320 ft.

The system discharge = 989 gpm.

The size of lateral = 6-5/8 inches.

The length of lateral = 1,290 ft.

The gross depth of application = 1.25 inches.

Time per revolution = 72 hours.

Design: (1) Select sprinklers and the end gun pressure.

Rain Bird 30-W-TNT-7/32 inch is the sprinkler type. This is a medium sized sprinkler which is suitable to operate at a medium pressure, so the pressure at the end gun is 50 psi.

(2) Determine the pressure distribution and sprinkler discharge.

Referring to Example 13: the pressure difference between the pivot and the end gun is

$$P_p - P_g = 14.9 \text{ psi}$$

A convenient way to represent the pressure distribution is to specify the pressure first and to find the associated radial distance. Such a representation is more suitable for application than the representation shown in Example 13.

Range of pressure in psi	Nominal Pressure in psi	Range of distribution factor D_F	Range of r/R from Fig. 9	Range of radial distance, r	Sprinkler discharge q, gpm
50-52.5	50	0-.168*	1.00-.550**	1320-726***	9.88
52.5-57.5	55	.168-.503	.550-.285	726-376	10.30
57.5-62.5	60	.503-.839	.285-.090	376-119	10.60
62.5-67.5	65	.839-1.00	.090-0	119-0	10.95

* $D_F = (P_r - P_g)/(P_p - P_g) = (52.5 - 50.0)/14.9 = 0.168$

** Enter $D_F = 0.168$ into Fig. 9 to obtain r/R = 0.550

*** r = 1320 (0.550) = 726 ft

The values of sprinkler discharge are obtained by entering the representative pressure into the sprinkler catalog from Rain Bird 30-W-TNT-7/32" sprinkler.

(3) Determine the radial distance and the spacing for sprinklers

Index of sprinkler	r_u in feet	Pressure P_r, psi from part (2)	Discharge q_d, gpm referring to part (2)	r_d in feet by Eq. (32)	Spacing S_s, feet by Eq. (33)
1	0	65	10.95	98	98
2	98[a]	60[b]	10.60	169[c]	71[d]
3	169	"	"	217	48
4	217	"	"	256	39
5	256	"	"	290	34
6	290	"	"	321	31
7	321	"	"	349	28
8	349	"	"	375	26
9	375	55	10.38	399	24
10	399	"	"	421	22
11	421	"	"	442	21
12	442	"	"	462	20
13	462	"	"	481	19
14	481	"	"	500	19
15	500	"	"	518	18
16	518	"	"	535	17
17	535	"	"	552	17
18	552	"	"	568	16
19	568	"	"	584	16
20	584	"	"	599	15
21	599	"	"	614	15
22	614	"	"	629	15
23	629	"	"	643	14
24	643	"	"	657	14
25	657	"	"	671	14
26	671	"	"	684	13
27	684	"	"	697	13
28	697	"	"	710	13
29	710	"	"	723	13
30	723	50	9.88	735	12
31	735	"	"	747	12
32	747	"	"	759	12
33	759	"	"	770	11
34	770	"	"	781	11
35	781	"	"	792	11
36	792	"	"	803	11

To be continued on next page

a The value of r_u for this sprinkler is the same in value as r_d for the upstream sprinkler.

b The value of r_d is to be larger than 119 ft so referring to part (2) P_r is 60 psi.

c $r_d^2 = 98^2 + (10.95 + 10.60) \cdot 1{,}320^2\ (989)$, $r_d = 169$ ft.

d $S_s = 169 - 98 = 71$ ft.

Index of sprinkler	r_u in feet	Pressure P_r, psi from part (2)	Discharge q_d, gpm referring to part (2)	r_d in feet by Eq. (32)	Spacing S_s, feet by Eq. (33)
37	803	50	9.88	814	11
38	814	"	"	824	10
39	824	"	"	835	11
40	835	"	"	845	10
41	845	"	"	855	10
42	855	"	"	866	11
43	866	"	"	876	10
44	876	"	"	885	9
45	885	"	"	895	10
46	895	"	"	905	10
47	905	"	"	914	9
48	914	"	"	924	10
49	924	"	"	933	9
50	933	"	"	943	10
51	943	"	"	952	9
52	952	"	"	961	9
53	961	"	"	970	9
54	970	"	"	979	9
55	979	"	"	988	9
56	988	"	"	996	8
57	996	"	"	1005	9
58	1005	"	"	1014	9
59	1014	"	"	1022	8
60	1022	"	"	1031	9
61	1031	"	"	1039	8
62	1039	"	"	1048	9
63	1048	"	"	1056	8
64	1056	"	"	1064	8
65	1064	"	"	1072	8
66	1072	"	"	1080	8
67	1080	"	"	1088	8
68	1088	"	"	1096	8
69	1096	"	"	1104	8
70	1104	"	"	1112	8
71	1112	"	"	1120	8
72	1120	"	"	1128	8
73	1128	"	"	1135	7
74	1135	"	"	1143	8
75	1143	"	"	1151	8
76	1151	"	"	1158	7
77	1158	"	"	1166	8
78	1166	"	"	1173	7
79	1173	"	"	1180	7
80	1180	"	"	1188	8
81	1188	"	"	1195	7
82	1195	"	"	1202	7
83	1202	"	"	1210	8
84	1210	"	"	1217	7

To be continued on next page

Index of Sprinkler	r_u in feet	Pressure P_r, psi from part (2)	Discharge q_d, gpm referring to part (2)	r_d in feet by Eq. (32)	Spacing S_s, feet by Eq. (33)
85	1217	50	9.88	1224	7
86	1224	"	"	1231	7
87	1231	"	"	1238	7
88	1238	"	"	1245	7
89	1245	"	"	1252	7
90	1252	"	"	1259	7
91	1259	"	"	1266	7
92	1266	"	"	1273	7
93	1273	"	"	1279	6
94	1279	"	"	1286	7
			Sum = 943.6		

(4) End gun. The sum of the sprinkler discharges listed in part (3) is 943.6 gpm, which does not check with the system discharge of 989 gpm. The reason is the same as the described in the previous example. The area associated with the outside strip not covered by the sprinklers listed in part (3) is by Equation (31)

$$Q = 453\ \pi\ \{1320^2 - (1286 + 7/2)^2\}\ 1.25/43560\ (72) = 45.1 \text{ gpm}$$

The additional discharge can be provided by an end gun "Rain Bird 85-EW-PS-15/32".

5.6 Re-nozzling

When the surface runoff becomes a serious problem after the center pivot system has been installed, a simple solution is to change the sprinklers so that the water is applied at a slower rate. The process of changing sprinklers is referred to as re-nozzling. A reduction in the application rate is usually associated with an increase in pressure. High pressure can be controlled by a pressure reducing valve so that the pressure distribution remains approximately the same as that of the previous design. After the new pressure distribution is determined, the sprinklers are selected from a sprinkler catalog. The procedure is similar to that described in Example 18, except the position of sprinklers is already fixed on the lateral.

To extend the tecnique described in Example 18 to a variable spacing system, consider the irrigated area of a sprinkler with a radial distance r. Referring to Equation (26) this area is

$$a = 2\pi \left\{\tfrac{1}{2}\left(\frac{r_d + r}{2} + \frac{r_u + r}{2}\right)\right\}\left(\frac{r_d + r}{2} - \frac{r_u + r}{2}\right)/43560$$

$$= \pi \left\{\left(\frac{r_d + r}{2}\right)^2 - \left(\frac{r_u + r}{2}\right)^2\right\}/43560 \qquad ---- (35)$$

where a = the irrigated area of a sprinkler in a variable spacing system, in acres,

r_d = the radial distance of the downstream sprinkler in feet,

r_u = the radial distance of the upstream sprinkler in feet.

The sprinkler discharge referring to Equation (7) is

$$q = 453\,\pi \left\{\left(\frac{r_d + r}{2}\right)^2 - \left(\frac{r_u + r}{2}\right)^2\right\} D_G/43560\ T_r \qquad ---- (36)$$

Divide Equation (36) by (28) to obtain

$$q = Q \left\{\left(\frac{r_d + r}{2}\right)^2 - \left(\frac{r_u + r}{2}\right)^2\right\}/R^2 \qquad ---- (37)$$

The procedure of re-nozzling is summarized as follows:

(1) Determine the new system discharge.

(2) Determine the new pressure distribution.

(3) Calculate the discharge of the new sprinklers by Equation (37).

(4) Select the sprinklers from a sprinkler catalog.

Example 20: Re-nozzling the center pivot system described in Example 19. Let the time per revolution be increased from 72 hours to 96 hours so that the application rate is reduced.

(1) System discharge. From Equation (28)

$$Q = 453\,\pi\,(1320)^2\ 1.25/43560\ (96) = 741.2 \text{ gpm}$$

(2) Pressure distribution, From Figure 7, the friction loss of an associated supply line with Q = 741.2 gpm, D = 6-5/8 inches and L = 1,290 ft is

$$H_f/100\ ft = 3.65\ ft$$

$$H_f = 3.65\ (1{,}290/100) = 47.1\ ft$$

The friction loss of the lateral is by Equation (9)

$$h_1 = 0.543\ (47.1) = 25.6\ ft$$

The pressure difference between the pivot and the end gun is by Equation (16)

$$P_p - P_g = 25.6/2.31 = 11.1\ psi$$

Let the pressure at the end gun be adjusted to 50 psi (same as Example 19) by a pressure reducing value. The new pressure distribution is represented by

Range of Pressure in psi	Nominal pressure in psi	Range of distribution factor, D_F	Range of r/R by Fig. 9	Range of radial distance, r
50-52.5	50	0-.225*	1.00-.492	1320-649**
52.5-57.5	55	.225-.676	.492-.180	649-238
57.5-62.5	60	.676-1.00	.180-0	238-0

* $D_F = (52.5-50)/11.1 = 0.225$

** $r = 0.492\ (1320) = 649$

(3) Sprinkler selection

Sprinkler index	$(r_d + r)/2$ in feet	Calculated discharge from Eq. (37)	Pressure P_r in psi	Sprinkler from catalog	Catalog discharge in gpm
1	133.5*	7.58**	60	30-CP-5/32"x3/32"	7.47
2	193	8.26***	55	30-CP011/64"x3/32"	8.25
3	236.5	7.95	"	"	8.25
4	273	7.91	"	30W-CP-3/16"	7.51
5	305.5	8.00	"	30-CP-11/64"x3/32"	8.25
6	335	8.04	"	"	8.25
7	362	8.01	"	30W-CP-3/16"	7.51
8	387	7.97	"	30-CP-11/64"x3/32"	8.25
9	410	7.80	"	30W-CP-3/16"	7.51
10	431.5	7.70	"	30-CP-11/64"x3/32"	8.25
11	452	7.70	"	30W-CP-3/16"	7.51
12	471.5	7.66	"	"	7.51
13	490.5	7.78	"	"	7.51
14	509	7.87	"	30-CP-11/64"x3/32"	8.25
15	526.5	7.71	50	"	7.87
16	543.5	7.51	"	30W-CP-3/16"	7.18
17	560	7.75	"	30-CP-11/64"x3/32"	7.87
18	576	7.73	"	"	7.87
19	591.5	7.70	"	"	7.87
20	606.5	7.64	"	30W-CP-3/16"	7.18
21	621.5	7.84	"	30-CP-11/64"x3/32"	7.87
22	636	7.76	"	"	7.87
23	650	7.66	"	"	7.87
24	664	7.83	"	"	7.87
25	667.5	7.70	"	"	7.87
26	690.6	7.57	"	30W-CP-3/16"	7.18
27	703.5	7.71	"	30-CP-11/64"x3/32"	7.87
28	716.5	7.85	"	"	7.87
29	729	7.69	"	"	7.87
30	741	7.50	"	30W-CP-3/16"	7.18
31	753	7.63	"	30-CP-11/64"x3/32"	7.87
32	764.5	7.42	"	30W-CP-3/16"	7.18
33	775.5	7.21	"	"	7.18
34	786.5	7.31	"	"	7.18
35	797.5	7.41	"	"	7.18
36	808.5	7.51	"	30-CP-11/64"x3/32"	7.87
37	819	7.27	"	30W-CP-3/16"	7.18
38	829.5	7.36	"	"	7.18
39	840	7.46	"	30-CP-11/64"x3/32"	7.87

To be continued on next page

* Referring to Example 19. $(r_d + r)/2 = (169 + 98)/2 = 133.5'$

** $q = 741.2\ (133.5^2 - 0^2)/1320^2 = 7.58$ gpm

*** $q = 741.2(193^2 - 133.5^2)/1320^2 = 8.26$ gpm

Sprinkler index	$(r_d + r)/2$ in feet	Calculated discharge from Eq. (37)	Pressure P_r in psi	Sprinkler from catalog	Catalog discharge in gpm
40	850	7.19	70	30W-CP-3/16"	7.18
41	860.5	7.64	"	30-CP-11/64"x3/32"	7.87
42	871	7.73	"	"	7.87
43	880.5	7.08	"	30W-CP-3/16"	7.18
44	890	7.15	"	"	7.18
45	900	7.61	"	"	7.18
46	909.5	7.31	"	"	7.18
47	919	7.39	"	"	7.18
48	928.5	7.47	"	"	7.18
49	938	7.54	"	30-CP-11/64"x3/32"	7.87
50	947.5	7.62	"	"	7.87
51	956.5	7.29	"	30W-CP-3/16"	7.18
52	965.5	7.36	"	"	7.18
53	974.5	7.43	"	"	7.18
54	983.5	7.50	"	30-CP-11/64"x3/32"	7.87
55	992	7.14	"	30W-CP-3/16"	7.18
56	1000.5	7.70	"	30-CP-11/64"x3/32"	7.87
57	1009.5	7.70	"	30-CP-11/64"x3/32"	7.87
58	1018	7.33	"	30W-CP-3/16"	7.18
59	1026.5	7.39	"	"	7.18
60	1035	7.45	"	"	7.18
61	1043.5	7.52	"	30-CP-11/64"x3/32"	7.87
62	1052	7.58	"	"	7.87
63	1060	7.19	"	30W-CP-3/16"	7.18
64	1068	7.24	"	"	7.18
65	1076	7.30	"	"	7.18
66	1084	7.35	"	"	7.18
67	1092	7.41	"	"	7.18
68	1100	7.46	"	30-CP-11/64"x3/32"	7.87
69	1108	7.51	"	"	7.87
70	1116	7.57	"	30W-CP-3/16"	7.18
71	1124	7.62	"	30-CP-11/64"x3/32"	7.87
72	1131.5	7.20	"	30W-CP-3/16"	7.18
73	1139	7.24	"	"	7.18
74	1147	7.78	"	30-CP-11/64"x3/32"	7.87
75	1154.5	7.34	"	30W-CP-3/16"	7.18
76	1162	7.39	"	"	7.18
77	1169.5	7.44	"	30-CP-11/64"x3/32"	7.87
78	1176.5	699	"	30W-CP-3/16"	7.18
79	1184	7.53	"	"	7.18
80	1191.5	7.58	"	30-CP-11/64"x3/32"	7.87
81	1198.5	7.12	"	30W-CP-3/16"	7.18
82	1206	7.67	"	"	7.18
83	1213.5	7.72	"	30-CP-11/64"x3/32"	7.87
84	1220.5	7.25	"	30W-CP-3/16"	7.18
85	1227.5	7.29	"	"	7.18
86	1234.5	7.33	70	30W-CP-3/16"	7.18

To be continued on the next page

Sprinkler index	$(r_d + r)/2$ in feet	Calculated discharge from Eq. (37)	Pressure P_r in psi	Sprinkler from catalog	Catalog discharge in gpm
87	1241.5	7.37	70	"	7.18
88	1248.5	7.41	"	30-CP-11/64"x3/32"	7.87
89	1255.5	7.46	"	30W-CP-3.16"	7.18
90	1262.5	7.50	"	30-CP-11/64"x3/32"	7.87
91	1269.5	7.54	"	30W-CP-3/16"	7.18
92	1276	7.04	"	"	7.18
93	1282.5	7.07	"	30W-CP-3/16"	7.18
94	1289.5	7.66	"	30-CP-11/64"x3/32"	7.87
					707.5*

* Sum of the discharges of the sprinklers

(4) End gun. The range covered by the sprinklers listed in the table extends to a radial distance of 1290.5 ft. (referring to the last value on the second column). The discharge associated with the area beyond its range is by Equation (29)

$$q = 2\ (741.2)\ \left(\frac{1320 + 1289.5}{2}\right)(1320 - 1289.5)/1320^2$$

$$= 33.9 \text{ gpm}$$

This discharge can be provided by an end gun"Rain Bird 85-EW-PS-13/32." (q = 33.3 gpm). The total discharge is

$$Q = 707.5 + 33.3 = 740.8 \text{ gpm}$$

which checks favorable with the system discharge of 741.2 gpm.

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