THE EFFECT OF SLOPE AND VARYING SPRINKLER DISCHARGE ON F FACTORS FOR SPRINKLER LATERAL DESIGN

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Bachelor of Science

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1950

Submitted to the faculty of the Graduate
School of the Oklahoma State University
in partial fulfillment of the
requirements for the degree
of
MASTER OF SCIENCE
August, 1965

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DISCHARGE ON F FACTORS FOR SPRINKLER
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PREFACE

The experimental work performed for this thesis research project was an analytical study of the effect of slope and varying sprinkler discharge on F factors for sprinkler lateral design. The study was programmed in 1620 FORTRAN for execution on the IBM 1620 electronic computer.

A number of tables, charts, and nomographs have been developed to assist the irrigation system designer in approximating friction losses occurring in sprinkler laterals. Most of these "design aids" have assumed all the sprinklers on the lateral to have the same discharge, and the lateral line to be laid out on the level. In actual application, friction losses and changes in elevation along a lateral line affect pressures, which in turn affect sprinkler discharge.

The results presented in this study should be of help to irrigation systems designers by providing them with F factors more nearly paralleling actual field conditions. This should enable them to do a better job of designing efficient sprinkler irrigation systems.

The author is grateful to Dr. James E. Garton, Professor of Agricultural Engineering; and to

Mr. Franklin R. Crow, Associate Professor of Agricultural Engineering, for their valuable assistance and guidance. Indebtedness is also acknowledged to Mr. Albert L. Mink, Research Assistant in Agricultural Engineering, for his assistance with computer programming involved in this study.

TABLE OF CONTENTS

LIST OF TABLES

Table | Page

LIST OF FIGURES

Figure		Page

CHAPTER I

INTRODUCTION

Irrigation may be defined as the artificial application of water to supply the moisture essential for crop production. Irrigation may be the sole source of water for crops in arid regions, or may be used to supplement natural rainfall in more humid areas.

Methods of irrigation may be classified into one of three categories: border or furrow irrigation, sprinkler irrigation, and sub-surface irrigation. Border, furrow and sub-surface irrigation methods have specific geological and topographic conditions that must be met before efficient application of water is possible.

Among the advantages of sprinkler irrigation, compared to other methods of irrigation, is the fact that since the water is transported by pipe until it is discharged from the sprinkler nozzle, it is possible to irrigate soils where the topography and/or soil type is/are not suitable to other methods of irrigation. In some of the more humid areas, irrigation can be profitable, however, the cost of land conditioning for border or furrow irrigation exceeds the benefits received. Frequently, these same soils can be profitably irrigated with a properly designed sprinkler irrigation system. Topographic slope often becomes involved in the design, and this creates complicated calculations requiring much time and effort.

A number of tables, charts, and nomographs have been developed to assist the irrigation system designer to approximate friction losses occurring in sprinkler laterals. Two assumptions are commonly made when these "design aids" are used. First, it is assumed that all sprinklers along the lateral have the same discharge. Sprinkler discharge varies directly as the square root of the pressure. Since friction losses do occur in the sprinkler lateral, pressure will vary from one sprinkler to the next. It is a common design practice to limit the friction loss occurring between the first and distal sprinklers on the lateral to 20 per cent of the entering pressure. On a level lateral, this means the least sprinkler discharge will be about 89 per cent of the greatest sprinkler discharge occurring along the line.

The second assumption usually made when developing sprinkler irrigation "design aids" is the sprinkler lateral is laid out on the level, i.e., there is no change in elevation along the sprinkler lateral. In actual application, very seldom does such a situation occur. Sprinkler irrigation design problems frequently involve slopes, and this entails complicated calculations requiring much time and effort.

Profitable irrigation begins with an efficient irrigation system. To be efficient, an irrigation system must be properly designed. Any methods for making reasonably accurate estimates of pressure variations are welcomed by sprinkler irrigation system designers.

CHAPTER II

OBJECTIVE

The analytical study was conducted for the following purposes:

1. To investigate the effect topographic slope and varying sprinkler discharge have on F factors used for approximating friction losses in sprinkler irrigation laterals.

2. To determine a set of values for factors R_1 and R_2 by which the actual friction loss and the pressure change due to slope respectively can be multiplied to determine the difference in pressure between the pressure entering the lateral and the average sprinkler operating pressure.

The following limitations were imposed on the study:

1. Slopes under consideration were limited to those within the range of +20% to -20%, with changes in slope being incremented at 5% intervals. Slopes were considered positive when the elevation increased from the source to the distal outlet on the sprinkler lateral.

2. Pipe diameters included in the study were limited to 3 inch, 4 inch, and 5 inch outside diameters, as these are the more common sizes used in sprinkler lateral design.

3. Sprinkler capacities were limited to 3 gpm (gallons per minute), 6 gpm, 9 gpm, and 12 gpm, as these effectively cover the range of capacities commonly used in systems design.

4. A pressure variation of 30% of the pressure at the distal sprinkler was allowed. Maintaining a pressure of 60 psi (pounds per square inch) at the distal sprinkler, limited pressure at the source of the lateral to 85.7 psi when slopes were positive, and to 42.0 psi when slopes were negative.

5. When the pressure at the source did not limit the number of sprinklers, the maximum number of sprinklers per lateral was limited to 50. For a 30-foot sprinkler spacing, this limited the lateral to a total length of 1500 feet where the first sprinkler is located a full-space from the source, and to 1515 feet where the first sprinkler is located one-half space from the source. Either of these total lengths is sufficient to cover most design situations.

CHAPTER III

REVIEW OF LITERATURE CITED

F Factor Where First Sprinkler Is Full Sprinkler Spacing From Main Line

In 1942, Christiansen (1, p.66) published a table of F factors which were developed for the purpose of estimating actual friction losses occurring in a sprinkler lateral (Table I). As water is removed at uniform intervals, the friction loss actually occurring in a sprinkler lateral is less than the friction loss would be were the entire quantity of water carried to the end of the pipe before discharge. Multiplying the friction loss that would occur in non-branching flow by the F factor gives a reasonably accurate estimate of the actual friction loss that does occur in the sprinkler lateral.

Christiansen's F factors were based on Scobey's formula for computing friction loss.

$$H_f = \frac{K_s L V^{1.9}}{1{,}000 D^{1.1}} .$$

TABLE I

TABLE OF F FACTORS DEVELOPED BY CHRISTIANSEN

Number Outlets	m = 1.85	m = 1.90	m = 2.00
1	1.0	1.0	1.0
2	0.639	0.634	0.625
3	0.535	0.528	0.518
4	0.486	0.480	0.469
5	0.457	0.451	0.440
6	0.435	0.433	0.421
8	0.415	0.410	0.398
10	0.402	0.396	0.385
12	0.394	0.388	0.376
14	0.387	0.381	0.370
16	0.382	0.377	0.365
18	0.379	0.373	0.361
20	0.376	0.370	0.359
25	*0.371	*0.365	*0.354
30	0.368	0.362	0.350
35	0.365	0.359	0.347
40	0.364	0.357	0.345
50	0.361	0.355	0.343

* Interpolated from table.

where H_f = the total friction in terms of feet occurring in a length of pipe

L = the length of pipe in feet

V = the mean velocity in feet per second

D = the internal diameter of the pipe in feet

K_s = Scobey's coefficient of retardation which varies with the smoothness of pipe.

In deriving equations for calculating friction losses in multiple outlet pipe, Christiansen made the following assumptions:

1. If the pipe line is level, the pressure will be a minimum at the distal end of the line, and will increase gradually toward the source.

2. Sprinkler discharge varies directly as a function of pressure. However, the variation in discharge of sprinklers along a lateral line is ordinarily not great. To simplify the calculation of friction losses, it is assumed the discharge of each sprinkler on the lateral line is equal to the average discharge of all the sprinklers,

$$q_1 = q_2 = q_3 = q_a = \frac{Q}{N}$$

where q_1, q_2, and q_3 are discharges of the first, second, and third sprinklers respectively, and q_a is the average discharge of all sprinklers, and is equal to the total discharge Q divided by the total number of sprinklers N.

Scobey's equation can be written in a generalized form

$$H_f = \frac{K_1 L V^m}{D^n} \tag{2}$$

The mean velocity of flow in a pipe can be stated as

$$V = \frac{Q}{A} = \frac{Q}{\frac{\pi D^2}{4}} = \frac{K_2 Q}{D^2} \tag{3}$$

where V is the velocity in feet per second, A is the cross-sectional area of the pipe in square feet, and Q is the quantity of flow in cubic feet per minute.

Changing V by exponentiating it to the m power, equation 3 becomes

$$V^m = \frac{K_2{}^m Q^m}{D^{2m}}$$

and substituting this for V^m and combining K_1 and $K_2{}^m$, equation 2 becomes

$$H_f = \frac{KLQ^m}{D^{2m+n}}$$

The total friction loss occurring in pipes with equally spaced multiple outlets is equal to the sum of the losses between adjacent outlets. Letting S equal the spacing between sprinklers, and q_a equal the discharge at each sprinkler, the friction loss between the last two sprinklers at the distal end becomes

$$h_1 = \frac{KSq_a{}^m}{D^{2m+n}}$$

and the loss between the next two sprinklers is

$$h_2 = \frac{KS(2q_a)^m}{D^{2m+n}} = \frac{KSq_a{}^m 2^m}{D^{2m+n}}.$$

Similarly, the friction loss occurring between the Nth pair of sprinklers is

$$h_n = \frac{KSq_a^{m}N^{m}}{D^{2m+n}}.$$

The total friction loss occurring in a pipe with N number of outlets uniformly spaced becomes

$$H_f = \Sigma(h_1+h_2+h_3+\ldots+h_n) = \frac{KSq_a^{m}}{D^{2m+n}} \Sigma(1^m+2^m+3^m+\ldots+N^m). \qquad (4)$$

Substituting $\frac{L}{N}$ for S, $\frac{Q}{N}$ for q_a, and ΣN^m for $\Sigma(1^m+2^m+3^m+\ldots+N^m)$, equation 4 becomes

$$H_f = \frac{K}{D^{2m+n}}\left(\frac{L}{N}\right)\left(\frac{Q^m}{N^m}\right)\Sigma N^m = \frac{\Sigma N^m}{N^{m+1}}\left(\frac{KLQ^m}{D^{2m+n}}\right). \qquad (5)$$

Letting $\frac{\Sigma N^m}{N^{m+1}} = F$, equation 5 becomes

$$H_f = F\left(\frac{KLQ^m}{D^{2m+n}}\right). \qquad (6)$$

where m and n are appropriate Scobey exponents.

Based on Scobey's study of research relative to exponentiation of Q and D, the exponents of Q and D should total to a value of 3.0(2). That is, if m = 1.9, then $2^{m+n} = 1.1$.

Adjusted F factor Where First Sprinkler Is One-Half Sprinkler Spacing From Main Line

In 1957, Jensen and Fratini (3) published a table of F factors adjusted for the situation where the first sprinkler on a lateral is located one-half a sprinkler head spacing from the main, rather than a full sprinkler head spacing as used by Christiansen (Table II). They were interested in

TABLE II

TABLE OF ADJUSTED F FACTORS DEVELOPED BY JENSEN AND FRATINI

N	F		
Number Outlets	m = 1.75	m = 1.9	m = 2.0
1	1	1	1
2	0.532	0.512	0.500
3	0.455	0.434	0.422
4	0.426	0.405	0.393
5	0.410	0.390	0.378
6	0.401	0.381	0.369
8	0.390	0.370	0.358
10	0.384	0.365	0.353
12	0.380	0.361	0.349
14	0.378	0.358	0.347
16	0.376	0.357	0.345
18	0.374	0.355	0.343
20	0.373	0.354	0.342
25	*0.3715	*0.3515	*0.3405
30	0.370	0.350	0.339
40	0.368	0.349	0.338
50	0.367	0.348	0.337

* Interpolated from table.

determining what influence this change in design had on F factor values.

As did Christiansen, Jensen and Fratini used Scobey's formula for computing friction loss

$$H_f = \frac{K_s L Q^m}{D^{2m+n}}.$$

They made the assumption that all sprinklers along the lateral had the same discharge, just as Christiansen had assumed in his derivation of the equation for calculating F factors. Also, the lateral line was assumed to be laid on the level.

In making their derivation of the equation for calculating adjusted F factors, Jensen and Fratini started with the first sprinkler located one-half sprinkler head spacing from the lateral source, and worked toward the distal sprinkler. The friction loss occurring in the lateral between the main line and first sprinkler would be

$$H_{f_1} = \frac{K_s \frac{S}{2} (Nq)^m}{D^{2m+n}} \qquad (7)$$

where

K_s is Scobey's coefficient of retardation

S is the distance between sprinkler heads

N is the total number of sprinkler heads along the lateral

q is the average sprinkler discharge, and

m and n are appropriate Scobey exponents.

The friction loss occurring in the lateral between the first and second sprinklers would be

$$H_{f_2} = \frac{K_s S(N-1)^m q^m}{D^{2m+n}} \tag{8}$$

between the second and third sprinklers

$$H_{f_3} = \frac{K_s S(N-2)^m q^m}{D^{2m+n}} \tag{9}$$

between the third and fourth sprinklers

$$H_{f_4} = \frac{K_s S(N-3)^m q^m}{D^{2m+n}} \tag{10}$$

and so on until the friction loss between the last two sprinkler heads on the lateral becomes

$$H_{f_n} = \frac{K_s S(1)^m q^m}{D^{2m+n}}. \tag{11}$$

Combining these equations (7, 8, 9, 10 and 11) for the actual friction loss in each section of the lateral, a general equation can be written

$$H_f = \frac{K_s S N^m q^m}{2D^{2m+n}} + \frac{K_s S(N-1)^m q^m}{D^{2m+2}} + \frac{K_s S(N-2)^m q^m}{D^{2m+2}} + \frac{K_s S(N-3)^m q^m}{D^{2m+n^2}} + \ldots + \frac{K_s S(1)^m q^m}{D^{2m+n}}. \tag{12}$$

Substituting $\frac{L}{N}$ for S, and factoring out $\frac{K_s L q^m}{D^{2m+n}}$, the general equation (13) for multiple outlet flow becomes

$$H_{f_m} = \frac{K_s L q^m}{D^{2m+n}} \left[\frac{N^m}{2N} + \frac{(N-1)^m}{N} + \frac{(N-2)^m}{N} + \frac{(N-3)^m}{N} + \ldots + \frac{(1)^m}{N}\right].$$

The friction loss that would have occurred, if the quantity of water had been carried the full length of the lateral before discharge, would have been

$$H_f = \frac{K_s N^m q^m S}{2D^{2m+n}} + \frac{K_s N^m q^m (N-1) S}{D^{2m+n}}. \qquad (14)$$

Again substituting $\frac{L}{N}$ for S, and factoring out $\frac{K_s L q^m}{D^{2m+n}}$, equation (14) for single discharge becomes

$$H_{f_o} = \frac{K_s L q^m}{D^{2m+n}} \left[\frac{N^m}{2N} + \frac{N^m (N-1)}{N} \right].$$

By definition,

$$F = \frac{H_{f_m}}{H_{f_o}}.$$

Factoring out $K_s L q^m / D^{2m+n}$, the equation for F becomes

$$F = \frac{\frac{N^m}{2N} + \frac{1}{N} \left[(N-1)^m + (N-2)^m + (N-3)^m + \ldots + (1)^m \right]}{\frac{N^m}{2} + \frac{N^m (N-1)}{N}}.$$

By eliminating fractions in the numerator and denominator,

$$F = \frac{N^{m+1} + 2N \left[(N-1)^m + (N-2)^m + (N-3)^m + \ldots + (1)^m \right]}{N^{m+1} + 2N^{m+1}(N-1)}.$$

Dividing the equation into two parts,

$$F = \frac{N^{m+1}}{N^{m+1} + 2N^{m+1}(N-1)} + \frac{2N \left[(N-1)^m + (N-2)^m + (N-3)^m + \ldots + (1)^m \right]}{N^{m+1} + 2N^{m+1}(N-1)}$$

and cancelling out N^{m+1} in the first term, and N in the second term,

$$F = \frac{1}{1 + 2(N-1)} + \frac{2 \left[(N-1)^m + (N-2)^m + (N-3)^m + \ldots + (1)^m \right]}{N^m \; 1 + 2(N-1)}.$$

Multiplying out the terms in the denominator, and reducing to lowest possible terms, the equation for F for a lateral with the sprinkler located one-half sprinkler head spacing from the main becomes

$$F = \frac{1}{(2N-1)} + \frac{2}{(2N-1)N^m} \left[(N-1)^m + (N-2)^m + (N-3)^m + \ldots + (1)^m \right].$$

Jensen and Fratini found the adjustment in F factors due to relocation of the first sprinkler to be significant. The per cent correction ranged from about 25 per cent for two sprinklers on the lateral, to about 5 per cent for 20 sprinklers, to about 2 per cent for 50 sprinklers on the lateral, using a value of 1.9 for Scobey's exponent m.

Effect of Pressure and Sprinkler Discharge Capacity On Application Efficiency Under Windy Conditions

Wiersma (5) conducted a study on the effect of wind on the distribution of water from rotating sprinklers, the results of which were published in 1955. Certain of his conclusions from the study were taken under consideration when setting the specifications and limitations on operating pressures and sprinkler spacing.

Wiersma found that sprinklers operating at high pressures had better distribution patterns than sprinklers operating at low pressures. The selection of the allowable variation in operating pressure to be permitted along a sprinkler lateral must take into consideration the effect of pressure on both the sprinkler discharge and the distribution pattern. Greater pressure variation may be permissible, if the lowest sprinkler operating pressure occurring along the lateral is maintained above that minimum pressure necessary for producing a satisfactory distribution pattern.

In this study, the pressure variation was limited to 30 per cent of the main line pressure, and the pressure at the distal sprinkler was maintained at 60 psi. Both of these values are somewhat higher than those for the average system in Oklahoma.

In addition to the effect of pressure on distribution patterns, Wiersma found that as wind velocities increased above 4 miles per hour, sprinkler head spacings of 20 feet and 30 feet were superior to the 40-foot spacing which was accepted as standard. The distance the lateral was moved between irrigation settings was found to have an even greater influence on uniformity of application. Wind is frequently present in Oklahoma weather conditions; therefore, a sprinkler head spacing of 30 feet was used for the study.

Values for Scobey's Coefficient K_s

Ree (4), in 1959, published a compilation of research and data relative to friction losses occurring in quick coupled aluminum pipe used for sprinkler irrigation systems. He developed values for Scobey's coefficient for new pipe and very good used pipe, both without couplers; and suggests using $K_s = 0.31$ for 3-inch and 4-inch pipe in very good condition, and $K_s = 0.30$ for 6-inch pipe in very good condition.

Research has shown a considerable difference in the amount of resistance offered to water flowing through various designs of quick-couplers for aluminum pipe. A common practice is to add an amount to the pipe friction factor so that the coupler head loss will be included in the friction head-loss estimate. Ree developed a table of equivalent values of Scobey's K_s for coupler head loss (4, p. 17). This K_s for the coupler is added to the K_s value for the pipe. For couplers having average resistance to flow (K_c = 0.2) and a coupler spacing of 30 feet, he suggests using a coupler K_s value of 0.03 for 3-inch diameter pipe, and 0.05 for 5-inch diameter pipe.

CHAPTER IV

PROCEDURE

The study was programmed in 1620 FORTRAN for execution on the computer in the Engineering Computer Laboratory, College of Engineering, Oklahoma State University. The data processing system in the laboratory consists of an IBM 1620 electronic computer and an IBM 1622 Card Read-Punch. The FORTRAN programs and input data were punched on an IBM 26 Card Printing Punch machine. Programs, input data and output data were machine listed on an IBM 407 Accounting Machine. Core storage capacity of the IBM 1620 is limited to a maximum of 20,000. This limitation on core storage capacity made it necessary to separate the execution of the study into two distinct phases - first, computation of F factors; and second, computations of R_1 and R_2 factors.

Computations of F Factors

The F factor is the ratio of the pressure loss that occurs in a pipeline with multiple outlets, compared to the pressure loss that would have occurred had the same entering rate of flow been carried through the same length of pipe without outlets. The following factors affect the friction loss occurring in a pipe: the velocity of flow, the degree of roughness in the pipe, and the length of the pipe involved.

The F factors, as developed by Christiansen (1, p.66), and later adjusted by Jensen and Fratini (3, p.247), were based on an approximation using an equation involving only the number of sprinklers N and Scobey's exponent m. When the effect of slope is introduced into the hydraulic analysis of sprinkler laterals, it is necessary to calculate actual friction losses occurring, and to take into consideration the effect of the slope.

Since the study required determining the F factor by using actual friction losses, it was decided to maintain a constant pressure at the distal sprinkler. In this way it was possible to compute sprinkler discharge at succeeding sprinklers on the basis of the pressure at the preceding sprinkler, and correcting for change in pressure due to friction loss and slope occurring between the two sprinklers in question.

Disregarding the velocity head occurring in the sprinkler riser, as it is negligible, sprinkler capacity can be calculated by the following equation: $q = 38.00\ Ca\sqrt{P}$ where q is the discharge in gallons per minute, C is the coefficient of discharge for the particular design of nozzle, a is the cross-sectional area of nozzle opening in square inches, and P is the pressure at the sprinkler in pounds per square inch. Since all nozzles on a sprinkler line were of one design, the terms "38.00 Ca" became a constant value (A), and q varied proportionately with the square root of P. For distal sprinkler capacities of 3, 6, 9, and 12 gpm, the equation for deriving the values of A became $A = q/\sqrt{P}$, where q equals the sprinkler discharge in gallons per minute (3, 6, 9, 12 gpm), and P equals 60 psi. The values of A for the various sprinkler capacities (q) were:

for q = 3.0 gpm A = 3/7.745967 = 0.387299

for q = 6.0 gpm A = 6/7.745967 = 0.7745968

for q = 9.0 gpm A = 9/7.745967 = 1.161895

for q = 12.0 gpm A = 12/7.745967 = 1.549194

For sprinklers succeeding the distal sprinkler, their capacity (q) equals the proper constant (A) multiplied by the square root of the calculated pressure (P). This calculated pressure would equal the pressure at the preceding sprinkler, plus the friction loss occurring in the length of pipe between the sprinklers, plus adjustment for the effect of the difference in elevation of the two sprinklers.

Once sprinkler capacity was determined, it was possible to calculate the friction loss occurring in the sprinkler lateral by applying Scobey's equation

$$H_f = \frac{K_s L V^{1.9}}{1000\ D^{1.1}}$$

where H_f equals the friction loss in feet, K_s is the appropriate Scobey coefficient to compensate for the condition of the pipe, V is the velocity of flow in cubic feet per second, and D is the inside diameter of the pipe in feet. As sprinkler discharge is commonly stated in gallons per minute, and pipe diameters in inches, it was necessary to convert sprinkler discharge to cubic feet per second, and pipe diameters to feet.

One cubic foot per second equals 448.83 gallons per minute. Sprinkler discharge was converted from gallons per minute (gpm) to cubic feet per second (cfs), by multiplying the discharge in gpm by 0.002228, or (1/448.83).

Irrigation pipe diameters are usually stated in terms of outside diameters. Three inch diameter aluminum irrigation pipe normally has a wall thickness of 0.05 inch, thus having a true inside diameter of 2.90 inches (0.24167 feet). Four inch and five inch diameter pipes normally have a wall of 0.063 inch, giving true inside diameters of 3.874 inches (0.3228 feet) and 4.874 inches (0.4061 feet) respectively.

To arrive at the flow velocity (V) in feet per second (fps), it was necessary to convert the volume of flow from gallons per minute by multiplying by 0.002228, and dividing the resulting quantity by the cross-sectional area of the pipe in square feet:

$$V\ (\text{fps}) = \frac{0.002228 \times \text{gpm}}{\text{Pipe area (sq. ft.)}}$$

The cross-sectional area of 3-inch pipe is 0.04589 square feet, while 4-inch pipe has a cross-sectional area of 0.08188 square feet, and 5-inch pipe has a cross-sectional area of 0.12962 square feet.

Using Ree's suggested values of K_s for very good used aluminum pipe without couplers, and adding an equivalent value of K_s to compensate for coupler loss ($K_c = 0.2$), the following values of K_s were used to calculate the friction loss.

Pipe diameter (inches)	K_s (Pipe only)	K_s (Coupler)	K_s (Combined)
3	0.31	0.03	0.34
4	0.31	0.04	0.35
5	0.31	0.04	0.35

Substituting the values for K_s, V, and D, Scobey's equation for calculating friction loss in a one-foot section of 3 inch nominal diameter lateral becomes:

$$H_f \text{ (psi)} = \frac{(0.34)\left[(0.002228)(\text{gpm})/0.04589\right]^{1.9}}{1000\ (0.24167)^{1.1}\ (2.31)}$$

for 4-inch nominal diameter lateral:

$$H_f \text{ (psi)} = \frac{(0.35)\left[(0.002228)(\text{gpm})/0.08188\right]^{1.9}}{1000\ (0.3228)^{1.1}\ (2.31)}$$

for 5-inch nominal diameter lateral:

$$H_f \text{ (psi)} = \frac{(0.35)\left[(0.002228)(\text{gpm})/0.12962\right]^{1.9}}{1000\ (0.4061)^{1.1}\ (2.31)}$$

The friction loss occurring between two adjacent sprinklers could then be determined by multiplying the friction loss occurring in one foot of lateral by the sprinkler spacing in feet.

Topographic slopes are commonly expressed in terms of per cent. The per cent slope was calculated by dividing the amount of change in the verical direction by the horizontal distance over which this change occurred. These values are usually dimensioned in feet. For the purposes of the study, slopes were considered positive when the elevation increased as one moved from the source to the distal sprinkler.

In calculating the effect of slope on pressure changes in a lateral line, it is necessary to remember that the lateral line forms the hypotenuse of a right triangle composed of horizontal distance and rise or decline. Figure 1 shows a sketch of the condition that exists.

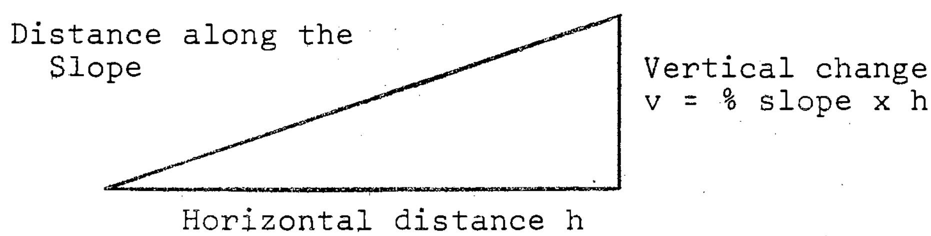

Figure 1. Triangular Relationships

To arrive at the elevation change occurring in one sprinkler spacing (30 ft.), the trigonometric solution of a right triangle was used. As the length of two sides of a right triangle were known, the length of the hypotenuse equaled the square root of the sum of the square of the two sides. Expressed in terms of h and per cent slope, with the per cent slope expressed as a decimal fraction, the hypotenuse = $\sqrt{h^2 + (\text{per cent slope} \times h)^2}$.

Substituting the numerical value of 100 for h, the hypotenuse = $\sqrt{(100)^2 + (\text{per cent slope})^2}$, where the per cent slope was expressed as a whole number.

Since the sprinkler lateral corresponded to the hypotenuse of a right triangle, it was possible to determine the change in elevation occurring in the distance spanned by one sprinkler spacing by using the simple ratio:

$$\frac{S}{\sqrt{(100)^2 + (\text{per cent slope})^2}} = \frac{v_s}{\text{per cent slope}}, \text{ or}$$

$$v_s = \frac{S}{\sqrt{(100)^2 + (\text{per cent slope})^2}} \times \text{per cent slope}$$

where S is the sprinkler spacing in feet, per cent slope is expressed as a whole number, and v_s is the vertical change occurring in the distance spanned (S).

Since sprinkler pressures and friction losses are commonly expressed in pounds per square inch, it was necessary to divide v_s by 2.31 to convert from feet to psi.

Once the formulas or equations had been developed in a manner compatible for computer execution, the FORTRAN program was written. Up to five alphabetic and/or numeric characters can be used to denote variables contained in the program. Certain restrictions do apply regarding the first alphabetic character contained in the variable. If the mathematical execution of statement involves a decimal point, the first letter in the variable name can be any letter except I, J, K, L, M, or N. Numbers containing decimal points are called floating point numbers. If decimal points are not necessary and it is not required to carry decimal fractions, fixed point numbers can be used (these numbers are expressed as whole numbers without a decimal point), and variable names must begin with any of the following letters: I, J, K, L, M, or N. It is not permissible to mix floating point and fixed point numbers in the same arithmetic calculations.

The FORTRAN program was written so as to carry out computations in the following sequence (Figures 2 and 3 in the Appendix).

1. Read into memory the value of A which is the constant for calculating sprinkler discharge, the pipe diameter, and the appropriate Scobey constant as K_S.
2. Initiate the per cent slope at 25.%, sprinkler pressure at 60.0 psi, quantity of flow at 0.0 gpm, pressure at source as 0.0 psi, number of sprinklers equal to 0.0, and friction loss as 0.0.
3. Increment the slope by subtracting five from the preceding value of S, which was initiated as 25.
4. Calculate the pressure change occurring due to the effect of slope.
5. Commence calculation of friction loss occurring in the multiple outlet lateral by incrementing the

number of sprinklers by one, and determining sprinkler discharge on the basis of the pressure at the preceding sprinkler, plus pressure correction to compensate for friction loss and change in elevation occurring between the two sprinklers.

6. Calculate total quantity of flow through pipe by summation of previous flow and the discharge quantity of the sprinkler added.

7. Calculate the velocity of flow occurring in the increment of pipe added, and calculate the friction loss occurring.

8. Calculate average pressure at sprinklers by dividing a summation of the pressure at sprinklers by the number of sprinklers.

9. Calculate pressure at the source of the lateral by adding the friction loss and pressure correction for elevation to the pressure occurring at the last sprinkler added.

10. Calculate the friction loss for the lateral by subtracting the pressure at the distal sprinkler and subtracting the pressure correction for elevation for the entire sprinkler lateral. This completes the process of determining the friction loss occurring in the lateral with multiple outlets.

11. Calculate the friction loss that would have occurred had the entire quantity of flow been carried to the

end of the lateral before discharging.

12. Have the machine punch desired output cards, or type desired output on console typewriter.

13. Next, a series of tests were carried out on the data.

    a. The program was designed to perform a test on the slope to see if the calculated pressure at the source was 42.0 psi or less. If the pressure was 42.0 psi or more, the program was directed to go to the next test.

    b. The next test was to see whether or not the program had iterated enough times to have 50 sprinklers on the lateral. If there were less than 50 sprinklers, the program proceeded to test for exceeding the maximum desired pressure at the source. If there were 50 sprinklers, the program was directed to test the slope to see if the calculations had covered from +20% to -20%.

    c. In the test of maximum pressure at the source (85.7 psi), if the test was negative, that is, the calculated pressure at the source was less than 85.7 psi, the program was directed to add another sprinkler and 30 feet of lateral pipe and to carry out the computations. If the source pressure equaled or exceeded 85.7 psi, the program was directed to carry out the test for the slope being within the desired range.

d. In the slope test, if the complete range had not been covered, the per cent slope was decreased by an increment of 5%, and calculations were started anew for a sprinkler lateral on a new per cent of slope. If the slope test resulted in a zero, the program was directed to read in a new data card with the appropriate values for pipe diameter, Scobey's value K_s, and A, which is the sprinkler coefficient for computing Q, and then proceed with calculations.

All that was needed to modify the program to change locations of the first sprinkler from a half-space from the source to a full space from the source was to change two cards in the program. One of these cards was for calculating the pressure at the source, and the other card was in the calculation of the total length of lateral line. Of course, when these cards were changed, it was necessary to compile another object deck in machine language.

Computation of R_1 and R_2 Factors

The computation of R_1 and R_2 factors was carried out to determine what factors could be multiplied times the actual friction loss occurring in a lateral and the pressure change due to slope, and thus estimate either the pressure at the source of the lateral or the average sprinkler pressure when one of these pressures is known. In the design of sprinkler systems on level terrain, it is common practice to calculate the friction loss that actually occurs and add three-fourths of this loss to the desired average sprinkler pressure to arrive at the pressure necessary at the source.

Based on some experimental calculations, it was thought that the pressure change due to slope should be multiplied by a factor of 0.5, and the resulting factor by which to multiply the friction loss would be approximately 0.75. The FORTRAN program was originally written to calculate an R factor by which the friction loss should be multiplied, using the following equation:

$$R = \frac{P_m - P_a - 0.5 \times PLSLO}{HLT}$$

where: P_m = Pressure at the source of the lateral

P_a = Average sprinkler pressure

PLSLO = Pressure change due to slope, and

HLT = Actual friction loss occurring in the sprinkler lateral.

It soon became apparent that the resulting R factors were not satisfactory. Since the program for calculating F factors already contained all the computations necessary, only slight modification was needed to produce the data needed for calculating the R factors. Principal changes were:

a. To have the computer subtract the average sprinkler pressure from the pressure at the source of the lateral, and store this value in memory.

$$(Y = P_m - P_a)$$

b. To have the computer punch or type the foregoing pressure difference (Y), the actual friction loss occurring in the lateral, and the pressure change due to slope.

Figures 4 and 5 in the Appendix are the FORTRAN programs used.

The procedure used in determining values for R_1 and R_2 was to calculate response surface that "best fit" or "best described" the surface that would be delineated had the values of Y, the actual friction loss, and the pressure change due to elevation been plotted on a three-dimensional graph. This plane of "best fit" was forced through the origin or zero. Natrella (6, p. 6-7) gives the following formulas for solving normal equations containing multivariable relationships:

$$B_1 \sum X_1^2 + B_2 X_1 X_2 = \sum X_1 Y$$

$$B_1 \sum X_1 X_2 + B_2 \sum X_2^2 = \sum X_2 Y$$

Solving these equations simultaneously for B_2, they become:

$$B_2 \frac{\sum X_1 X_2}{\sum X_1^2} + B_1 = \frac{\sum X_1 Y}{\sum X_1^2}$$

$$B_2 \frac{\sum X_2^2}{\sum X_1X_2} + B_1 = \frac{\sum X_2Y}{\sum X_1X_2}$$

or

$$B_2 \left[\frac{\sum X_1X_2}{\sum X_1^2} - \frac{\sum X_2^2}{\sum X_1X_2} \right] = \frac{\sum X_1Y}{\sum X_1^2} - \frac{\sum X_2Y}{\sum X_1X_2}$$

$$B_2 = \frac{\sum X_1Y - \sum X_2Y \left(\frac{\sum X_1^2}{\sum X_1X_2}\right)}{\sum X_1X_2 - \sum X_2^2 \left(\frac{\sum X_1^2}{\sum X_1X_2}\right)} \qquad (15)$$

Once a value for B_2 has been determined, it can be substituted into the equation

$$B_1 \sum X_1^2 + B_2X_1X_2 = \sum XY$$

and the equation solved for B_1.

$$B_1 = \frac{\sum X_1Y - B_2X_1X_2}{\sum X_1^2} \qquad (16)$$

These two basic equations (15) and (16) were used as shown in the FORTRAN program, except that the variable name R_1 was substituted for B_1, and R_2 was substituted for B_2.

The FORTRAN program (figure 6 in the Appendix) for determining values for R_1 and R_2 had the following sequence:

a. Read into memory the number of sets of data on which calculations are to be made.

b. Initiate the values of the sum of the squares and the cross-products as 0.0.

c. Read in set of data containing values for the difference between pressure at the source and the average sprinkler pressure (Y), the actual friction loss occurring (X_1) and the pressure change due to slope (X_2). As the data was read in, the following computations were carried out:

1. Summation of X_1 times Y
2. Summation of X_2 times Y
3. Summation of X_1 times X_2
4. Summation of $X_1{}^2$
5. Summation of $X_2{}^2$

d. After all data was read in and the above calculations performed, the sum of squares for X_2 was tested to see whether or not it were zero. If it were zero, R_1 was calculated, and the resulting values of R_1 and R_2 were punched into output cards. If the sum of the squares of X_2 were not zero, the program directed the computer to calculate values of R_1 and R_2, using equations (15) and (16), and then to punch the results into output cards.

The FORTRAN program for calculating values for R_1 and R_2 was so organized it could make calculations on the basis of either sprinkler capacity, diameter of lateral pipe, and slope, or any combination of these factors. All that was necessary was to determine the combination of factors, determine the number of sets of data involved, and to change the first data card N to the proper value for the number of data cards to be read.

Correction for Bias In Computing R_1 and R_2 Values

For one sprinkler operating on a lateral, the values of R_1 and R_2 are both unity, that is, the pressure at the source would equal the average sprinkler pressure plus the friction loss occurring, plus the pressure change due to elevation or slope. As additional sprinklers are added to the lateral, values for R_1 and R_2 decrease, with R_1 and R_2 approaching values of approximately 0.75 and 0.5 respectively. Since several of the sprinkler laterals, especially those at ±15% and ±20% slopes, had only from eight to fifteen sprinklers, the data on the first five sprinklers was not used in calculating R_1 and R_2. This adjusted the values downward from what they would have been had all data cards been used.

Determination of the Standard Deviation Using Calculated Values of R_1 and R_2

The standard deviation is probably the best known measure of variability. Standard deviation is the summation of the square of residual difference between observed and expected values divided by the degrees of freedom. Natrella (6, p.6-11) gives the following formula for calculating the deviation between predicted and observed values.

$$\widehat{Y} = R_1X_1 + R_2x2$$

$$r = Y - \widehat{Y}$$

where

$\hat{Y}$ is the predicted value

Y is the observed value, and

r is the residual.

Estimation of the variance, σ^2 can be made using the following equation (6, p.6-11).

$$\hat{\sigma}^2 = s^2 = \frac{1}{n-k} \sum r^2$$

where

$\hat{\sigma}^2$ is an estimate of the variance s^2

n is the number of observations

k is the number of variables involved, and

r is the residual between predicted and observed values.

Standard deviation, s, is the square root of the variance, or $s = \sqrt{\hat{\sigma}^2} = \sqrt{s^2}$ (6, p.6-11).

Execution of the FORTRAN program for calculating standard deviation had the following sequence of operation:

a. Read into memory values of R_1 and R_2 and the number of sets of data involved.

b. The sum of the residuals squared was initiated at 0.0.

c. The computer was directed to read values for the difference between the average sprinkler pressure and pressure at the lateral source, Y; the actual friction loss occurring, X_1; and the pressure change due to slope, X_2.

d. A value for the difference between average sprinkler pressure and pressure at the lateral source was calculated by multiplying R_1 times the friction loss occurring, X_1, and adding this to the value of the pressure change due to slope multiplied by R_2.

e. The difference between the read in value of the difference in pressure and the calculated difference in pressure was squared and summed.

f. Variance was computed and the standard deviation calculated as the square root of the variance.

g. Values for R_1 and R_2 and the standard deviation were punched into output data cards.

Figure 7 in the Appendix shows the FORTRAN program used.

CHAPTER V

RESULTS

The Effect of Varying Sprinkler Discharge On F Factors

The effect of varying sprinkler discharge on the calculated F factors for level laterals in the study can be determined by comparison with the F factors proposed by Christiansen and Jensen and Fratini. Table III lists the F factors proposed by Christiansen, the corresponding F factors calculated in the study, and the per cent change or difference of the calculated values from those of Christiansen. Table IV presents the same comparison of the calculated values to those proposed by Jensen and Fratini.

In the situation where the first sprinkler was located a full sprinkler head spacing from the main line, the variation ranged up to 1.97% between the calculated F factors and those proposed by Christiansen, with Christiansen's values being the greater of the two. This maximum variation occurred when 50 sprinkler heads were operating along the lateral. Since the F values calculated in the study took into consideration the effect of varying pressure on

TABLE III

COMPARISON OF CALCULATED F FACTOR VALUES WITH PUBLISHED VALUES BY CHRISTIANSEN

First sprinkler 30' from main
Scobey exponent m = 1.9
0% Slope

Number of Sprinklers	Christiansen	30'	Percent Change from Published Value
1	1.0	1.000	
2	.634	.633	0.16
3	.528	.529	0.19
4	.480	.479	0.21
5	.451	.451	0.0
6	.433	.432	0.23
8	.410	.410	0.0
10	.396	.396	0.0
12	.388	.387	0.26
14	.381	.381	0.0
16	.377	.376	0.27
18	.373	.371	0.54
20	.370	.368	0.54
25	*.365	.362	0.82
30	.362	.358	1.11
35	.359	.354	1.39
40	.357	.353	1.12
50	.355	.348	1.97

* Interpolated from table

TABLE IV

COMPARISON OF CALCULATED F FACTOR VALUES WITH PUBLISHED VALUES BY JENSEN & FRATINI

First sprinkler 15' from main
Scobey exponent m = 1.9
0% Slope

Number of Sprinklers	Jensen & Fratini	15'	Percent Change from Published Value
1	1.0	1.000	
2	.512	.511	0.20
3	.434	.434	0.0
4	.405	.405	0.0
5	.390	.390	0.0
6	.381	.381	0.0
8	.370	.370	0.0
10	.365	.364	0.27
12	.361	.360	0.28
14	.358	.358	0.0
16	.357	.355	0.56
18	.355	.353	0.56
20	.354	.352	0.56
25	*.3515	.349	0.85
30	.350	.348	0.57
35	.350	.345	1.43
40	.349	.345	1.15
50	.348	.342	1.72

* Interpolated from table

sprinkler discharge, whereas Christiansen assumed a constant discharge from each sprinkler, this variation can be attributed to the effect of varying sprinkler discharge. In the situation where the first sprinkler was one-half sprinkler spacing from the main line, the variation between the calculated F factors and those of Jensen and Fratini ranged up to a maximum of 1.72%, which also occurred with 50 sprinklers operating along the lateral. Here again, the calculated values were lower than those proposed by Jensen and Fratini, and this variation could be attributed to the effect of varying discharge.

The net effect of varying sprinkler discharge causes the F factor values proposed by Christiansen and Jensen and Fratini to overestimate the actual friction loss that will occur in a level lateral. As indicated by the following example, the amount of error induced was not appreciable, compared to the error that could occur from selecting the wrong value of Scobey's constant K_s. The maximum error induced by varying sprinkler discharge when using Christiansen's F value for 50 sprinklers was 1.97 per cent, and 1.72 per cent when using Jensen's and Fratini's F value. Selecting a value of 0.33 for Scobey's K_s, when it should have been 0.34, induced an error of 2.94 per cent, which was considerably greater than the error due to varying sprinkler discharge.

The Effect of Slope on F Factors

The effect of slope can probably best be estimated by comparing the calculated values of F over the range of slopes investigated, using some constant number of sprinklers operating on the lateral. Tables V and VI show the calculated F factors for varying numbers of sprinklers operating on laterals laid out along slopes within the range of +20 per cent to -20 per cent, in 5 per cent intervals. On laterals where the first sprinkler is 30 feet from the main line, the maximum variation for positive slopes (the lateral extending upslope from the main line) was a -3.94 per cent change from the F factor for the corresponding level lateral. The maximum variation of F factors for negative slopes (the lateral extending downhill from the main line) was a +4.51 per cent change. Where the first sprinkler was located 15 feet from the main line, the maximum variation was a -4.12 per cent change for positive slopes, and a +4.86 per cent change for negative slopes.

The per cent change indicated in Tables V and VI were determined by comparison of the calculated F value for a given slope, with the calculated F value for a level lateral with a corresponding number of sprinklers. Since all the F values calculated in the study included the effect for varying sprinkler discharge, the per cent change indicated can be attributed to the effect of slope.

TABLE V

CALCULATED VALUES OF F FACTOR AND PER CENT CHANGE FROM 0% SLOPE VALUES
FOR IRRIGATION LATERAL WITH FIRST SPRINKLER 30 FEET FROM MAIN LINE

	+20% Slope		+15% Slope		+10% Slope		+5% Slope		0%	-5% Slope		-10% Slope		-15% Slope		-20% Slope	
Number Outlets	F	Per Cent Change	F	Per Cent Change	F	Per Cent Change	F	Per Cent Change	F	F	Per Cent Change	F	Per Cent Change	F	Per Cent Change	F	Per Cent Change
1	1.000		1.000		1.000		1.000		1.000	1.000		1.000		1.000		1.000	
2	.631	-0.32	.631	-0.32	.632	-0.16	.633	0.0	.633	.635	+0.32	.636	+0.47	.637	+0.63	.637	+0.63
3	.524	-0.95	.525	-0.74	.526	-0.57	.528	-0.19	.529	.530	+0.19	.532	+0.57	.534	+0.95	.534	+0.95
4	.473	-1.25	.475	-0.84	.476	-0.63	.478	-1.21	.479	.482	+0.63	.483	+0.84	.485	+1.25	.487	+1.67
5	.443	-1.77	.445	-1.33	.447	-0.89	.449	-0.44	.451	.453	+0.44	.456	+1.11	.458	+1.55	.461	+2.22
6	.423	-2.08	.425	-1.62	.427	-1.16	.430	-0.46	.432	.435	+0.69	.438	+1.39	.439	+1.62	.444	+2.78
8	.398	-2.93	.400	-2.44	.403	-1.71	.406	-0.98	.410	.413	+0.71	.417	+1.71	.422	+2.93	.427	+4.15
10	.382	-3.54	.385	-2.78	.388	-2.02	.392	-1.01	.396	.401	+1.26	.406	+2.52	.412	+4.04		
12			.374	-3.36	.378	-2.33	.382	-1.29	.387	.393	+1.55	.399	+3.10				
14			.366	-3.94	.370	-2.89	.375	-1.57	.381	.387	+1.57	.395	+3.67				
16					.364	-3.19	.369	-1.86	.376	.383	+1.86	.391	+3.99				
18					.359	-3.23	.364	-1.89	.371	.380	+2.42	.386	+4.04				
20					.355	-3.53	.361	-1.90	.368	.378	+2.72	.383	+4.08				
25							.353	-2.49	.362	.374	+3.31	.376	+3.87				
30							.349	-2.51	.358	.371	+3.63	.366	+2.23				
35							.345	-2.54	.354	.366	+3.39	.355	+0.28				
40									.353	.363	+2.83	.355	+0.57				
50									.348	.353	+1.44						

TABLE VI

CALCULATED VALUES OF F FACTOR AND PER CENT CHANGE FROM 0% SLOPE VALUES
FOR IRRIGATION LATERAL WITH FIRST SPRINKLER 15 FEET FROM MAIN LINE

	+20% Slope		+15% Slope		+10% Slope		+5% Slope		0%	-5% Slope		-10% Slope		-15% Slope		-20% Slope	
Number Outlets	F	Per Cent Change	F	Per Cent Change	F	Per Cent Change	F	Per Cent Change	F	F	Per Cent Change	F	Per Cent Change	F	Per Cent Change	F	Per Cent Change
1	1.000		1.000		1.000		1.000		1.000	1.000		1.000		1.000		1.000	
2	.508	-0.59	.509	-0.39	.509	-0.39	.510	-0.20	.511	.514	+0.59	.514	+0.59	.515	+0.78	.516	+0.98
3	.429	-1.15	.430	-0.92	.432	-0.46	.433	-0.23	.434	.436	+0.46	.438	+0.92	.439	+1.15	.441	+1.61
4	.398	-1.73	.400	-1.23	.401	-0.99	.403	-0.49	.405	.407	+0.49	.409	+0.99	.412	+1.73	.414	+2.22
5	.381	-2.31	.383	-1.79	.385	-1.28	.388	-0.51	.390	.393	+0.51	.395	+1.28	.398	+2.05	.401	+2.82
6	.371	-2.62	.373	-2.10	.375	.1.57	.378	-0.79	.381	.384	+0.79	.387	+1.57	.390	+2.36	.394	+3.41
8	.357	-3.51	.360	-2.70	.363	-1.89	.367	-0.81	.370	.374	+1.08	.379	+2.43	.383	+3.51	.388	+4.86
10	.349	-4.12	.352	-3.30	.356	-2.20	.360	-1.10	.364	.369	+1.37	.375	+3.02	.381	+4.67		
12			.346	-3.89	.351	-2.50	.355	-1.39	.360	.366	+1.67	.373	+3.61				
14			.342	-4.47	.346	-3.35	.352	-1.68	.358	.365	+1.96	.373	+4.19				
16					.343	-3.38	.349	-1.69	.355	.363	+2.25	.371	+4.50				
18					.341	-3.40	.346	-1.98	.353	.363	+3.68	.368	+4.25				
20					.339	-3.69	.344	-2.27	.352	.362	+2.84	.367	+4.26				
25							.340	-2.58	.349	.361	+3.44	.363	+4.01				
30							.338	-2.87	.348	.361	+3.74	.356	+2.30				
35							.336	-2.61	.345	.357	+3.48	.345	0.0				
40									.345	.355	+2.90	.347	+0.57				
50									.342	.346	+1.17	.332	-2.92				

The Combined Effect of Varying Sprinkler Discharge and Slope on F Factors

The combined effect of varying sprinkler discharge and slope on F factors can be estimated by comparison of calculated values of F with corresponding values of F proposed by either Christiansen or Jensen and Fratini, depending upon the location of the first sprinkler in relation to the main line. For example, using a lateral laid on a +5 per cent slope and having 35 sprinklers operating, the calculated F value is 0.345. Christiansen's proposed F value for a lateral on the level with 35 outlets is 0.359. The per cent change between the calculated F value and Christiansen's value is 1.000 - (0.359/0.345), or -4.1 per cent. If this same lateral were laid out on a -5 per cent slope, the change from Christiansen's value would be +1.8 per cent. On laterals extending upslope, Christiansen's F value overestimated the friction loss by 4.1 per cent; and on laterals extending downslope, underestimated the friction loss by 1.8 per cent.

Making a similar comparison for a lateral laid on a +5 per cent slope and having 35 sprinkler heads, with the first sprinkler located 15 feet from the main line, it was found that using values proposed by Jensen and Fratini overestimated the friction loss by 4.1 per cent. Likewise, using their value on the same lateral laid on a -5 per cent slope underestimated the friction loss by 1.96 per cent. As shown in the following example, these per centages of error are not appreciable from the standpoint of design.

Assume that a lateral with 35 sprinklers is placed on a +5 per cent slope, and has an apparent friction loss of 9 psi. Using Christiansen's F value of 0.359, the estimated friction loss occurring was 3.23 psi. Using the F value for +5 per cent slope as calculated in this study, the estimated actual friction loss is 9.0 x 0.345 = 3.11 psi. The difference here anounts to only 0.12 psi. If the first sprinkler had been located 15 feet from the main line, the estimated friction loss using Jensen's and Fratini's F value of 0.350 was 3.15 psi, while using the calculated F value gave an estimated loss of 3.024 psi, or a difference of 0.126 psi.

With the same lateral placed on a -5 per cent slope, both Christiansen's and Jensen's and Fratini's F values resulted in estimated pressure losses of 0.09 psi less than the estimate using F values calculated in this study.

All of these differences due to using the various F values, 0.12 psi, 0.126 psi, and 0.09 psi, are so small in magnitude that usual design procedures are not accurate enough to become concerned with them.

The effect of both the number of sprinkler heads operating on a lateral and of slope are visually apparent in figures 8, 9. and 10.

The Effect of Slope on the Maximum Number of Sprinklers Operable on a Sprinkler Lateral

With only one exception, the maximum number of sprinklers that could be operated on a sprinkler lateral on a +20 per cent slope without exceeding the allowable 30 per cent pressure variation, was 10, regardless of lateral diameter or sprinkler capacity. The only exception was with the 3-inch diameter lateral with 3 gpm sprinklers, and here 11 sprinklers could be operated. The maximum number of sprinklers allowable on a lateral on a +15 per cent slope ranged from 12 to 14, with smaller sprinkler capacities allowing the greater number. On +10 per cent slopes, the allowable number of sprinklers ranged from 15 to 20. On slopes ranging from +5 per cent to -5 per cent, friction losses occurring in the lateral became the dominating factor in limiting the number of sprinklers permissible. On -15 per cent slopes, the number of sprinklers reduced to 10; and on -20 per cent slope, the maximum number of sprinklers was 8, regardless of sprinkler capacity or lateral diameter.

Figures 11, 12, and 13, show the number of sprinklers of various capacities that can operate on the given diameter of lateral without exceeding a 30 per cent pressure variation. In those cases where the number of sprinklers is 50, it is possible that a greater number could be operated on the

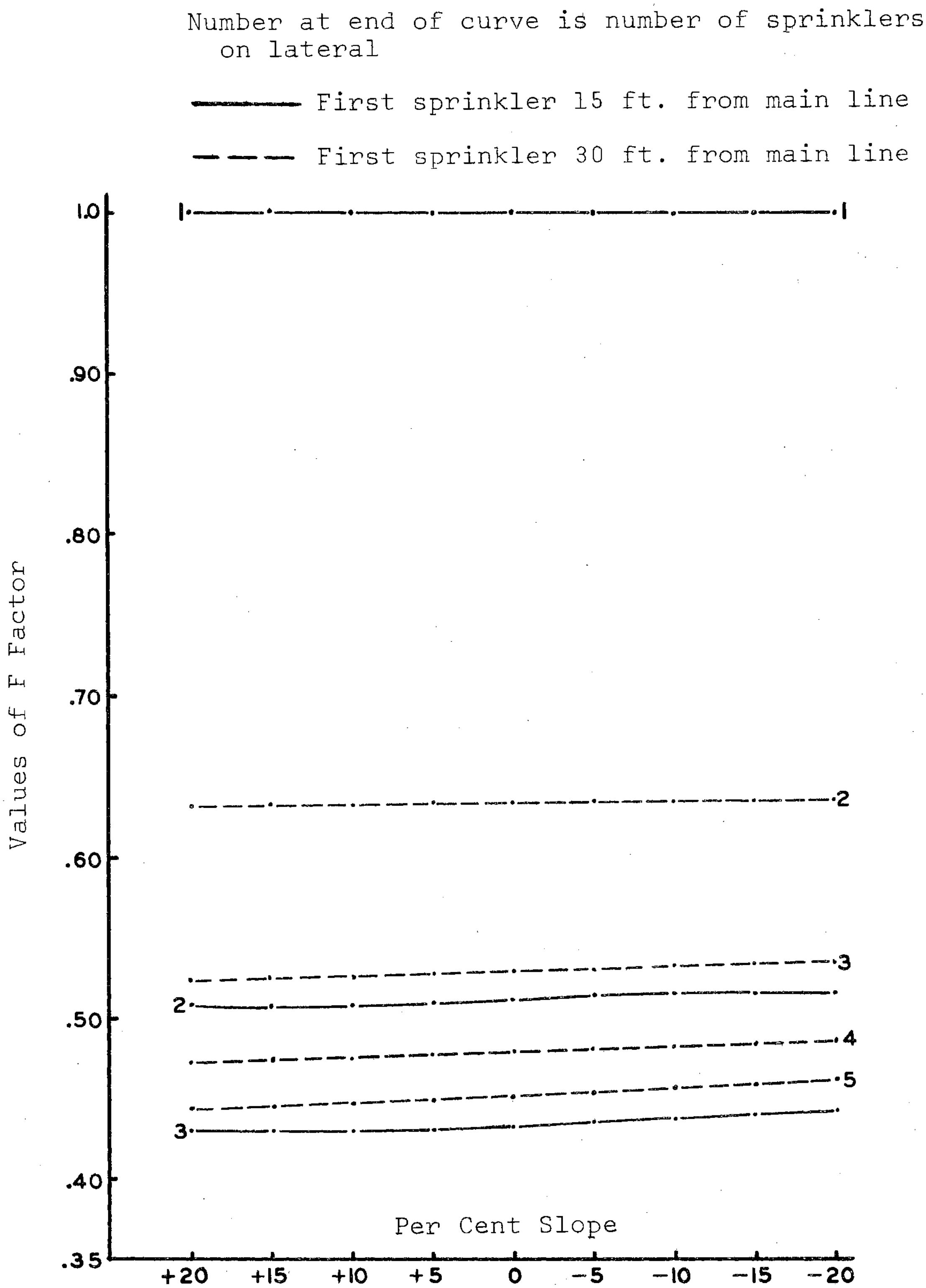

Figure 8. Effect of Slope on Values of F factor

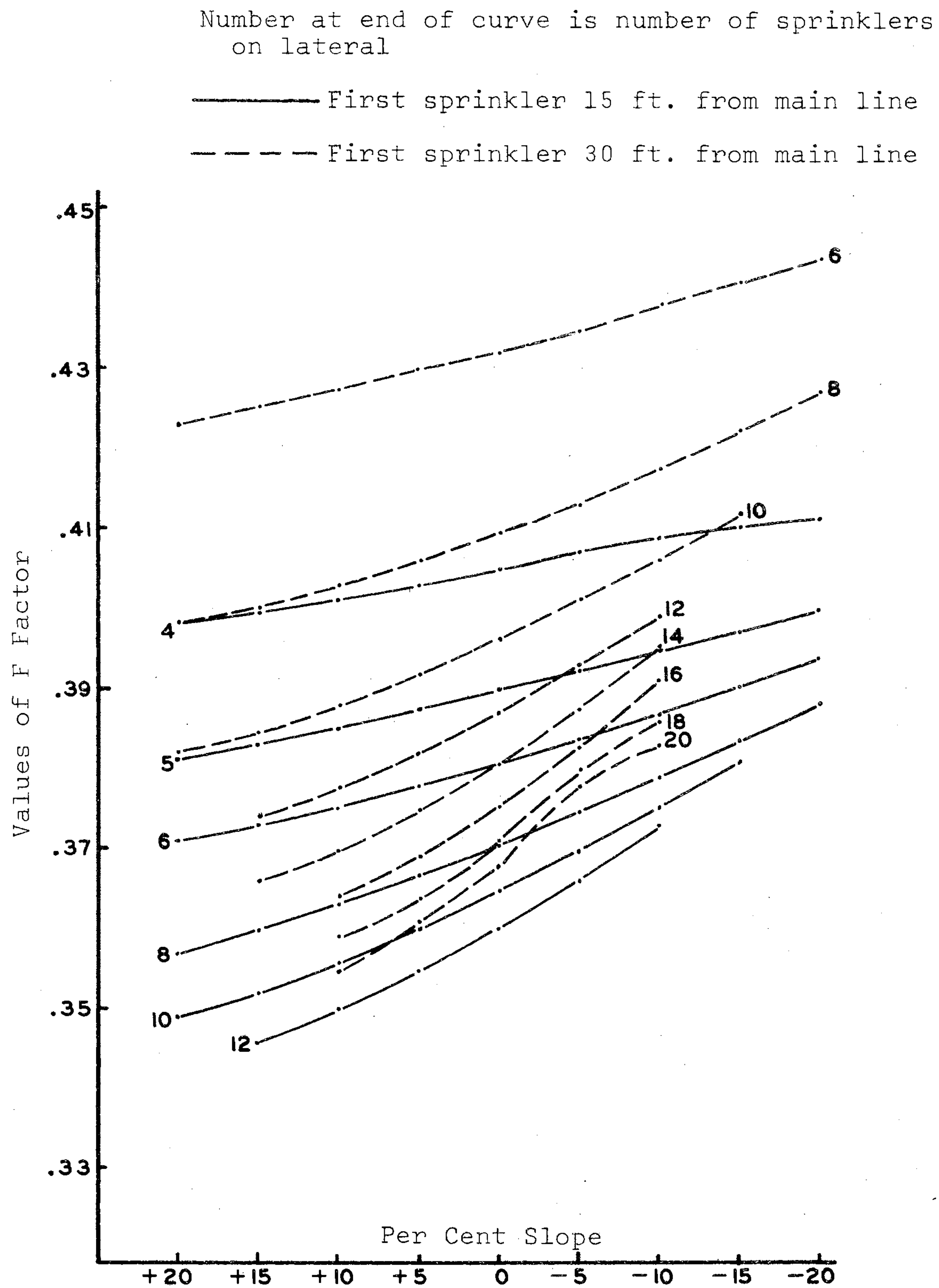

Figure 9. Effect of Slope on Values of F factor

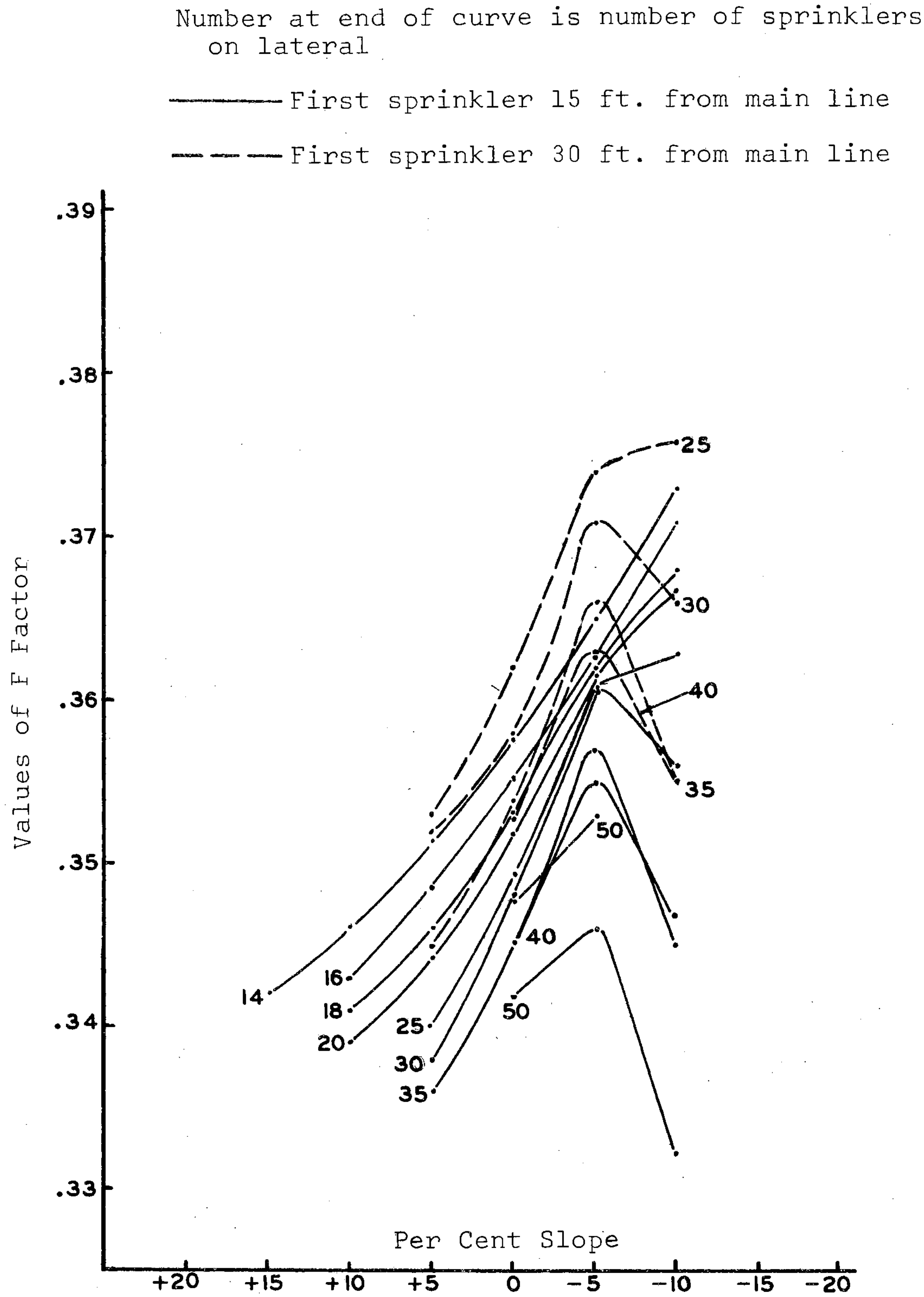

Figure 10. Effect of Slope on Values of F factor

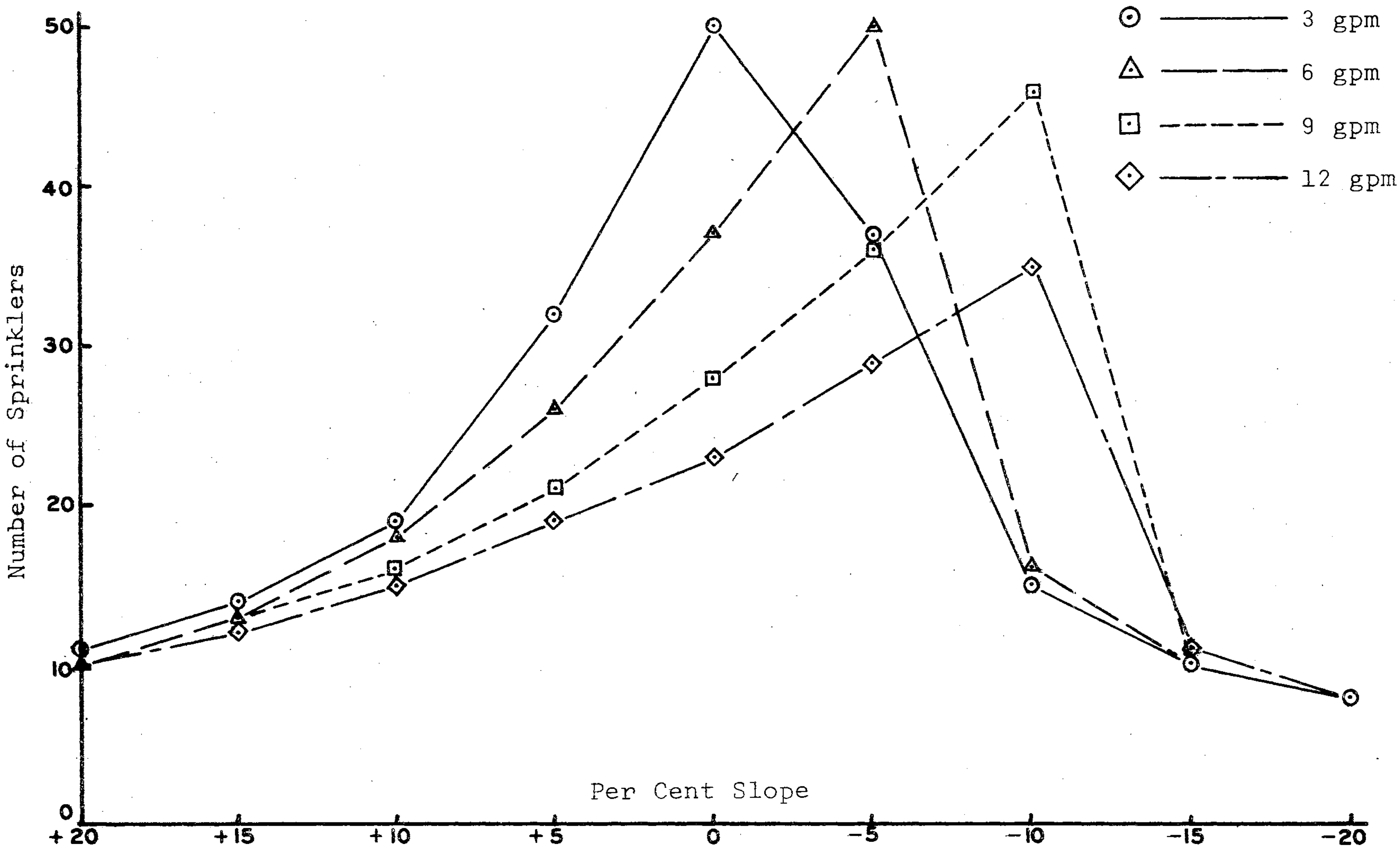

Figure 11. Effect of Slope on Maximum Number of Sprinklers For 3 inch Lateral

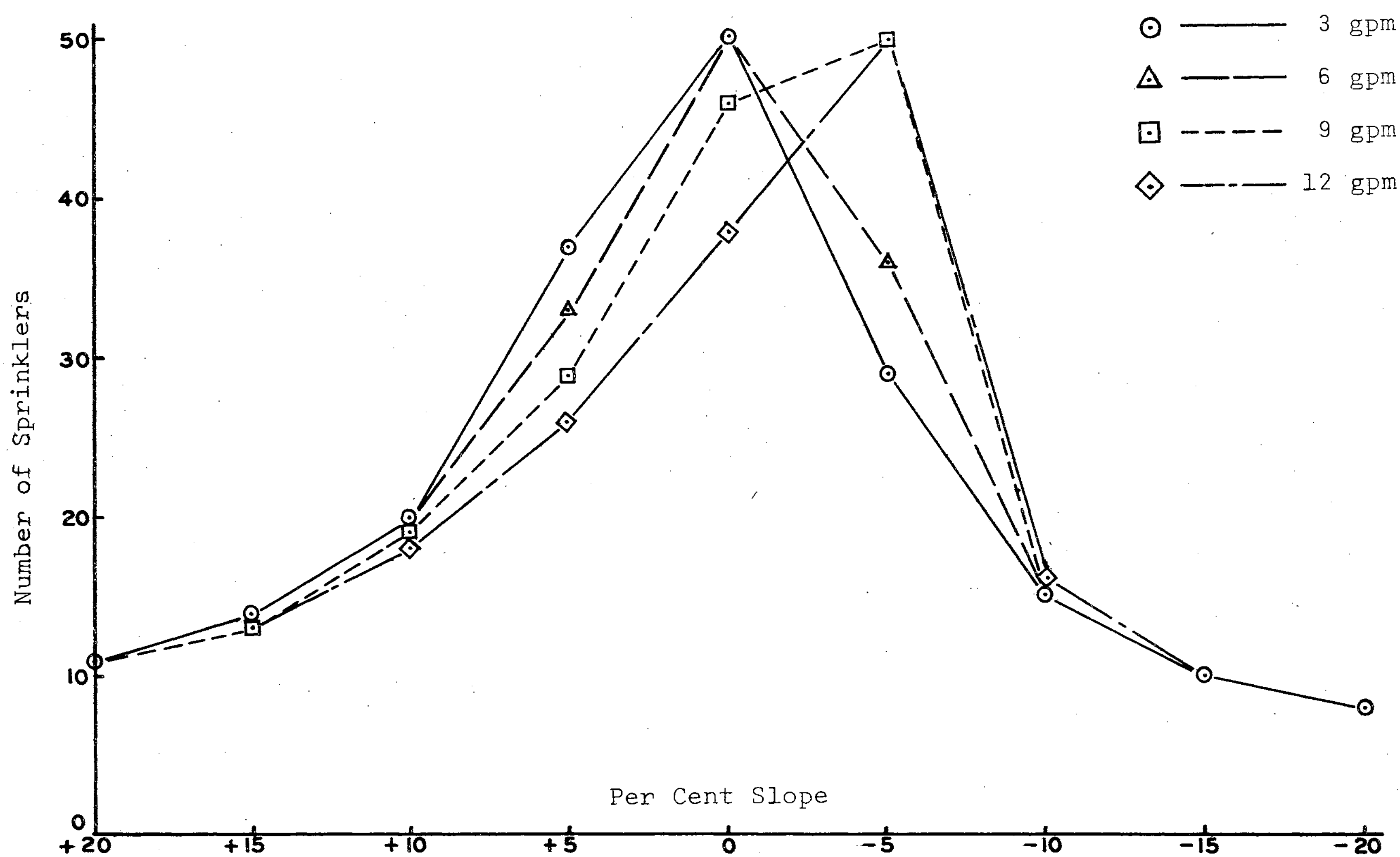

Figure 12. Effect of Slope on Maximum Number of Sprinklers For 4 inch Lateral

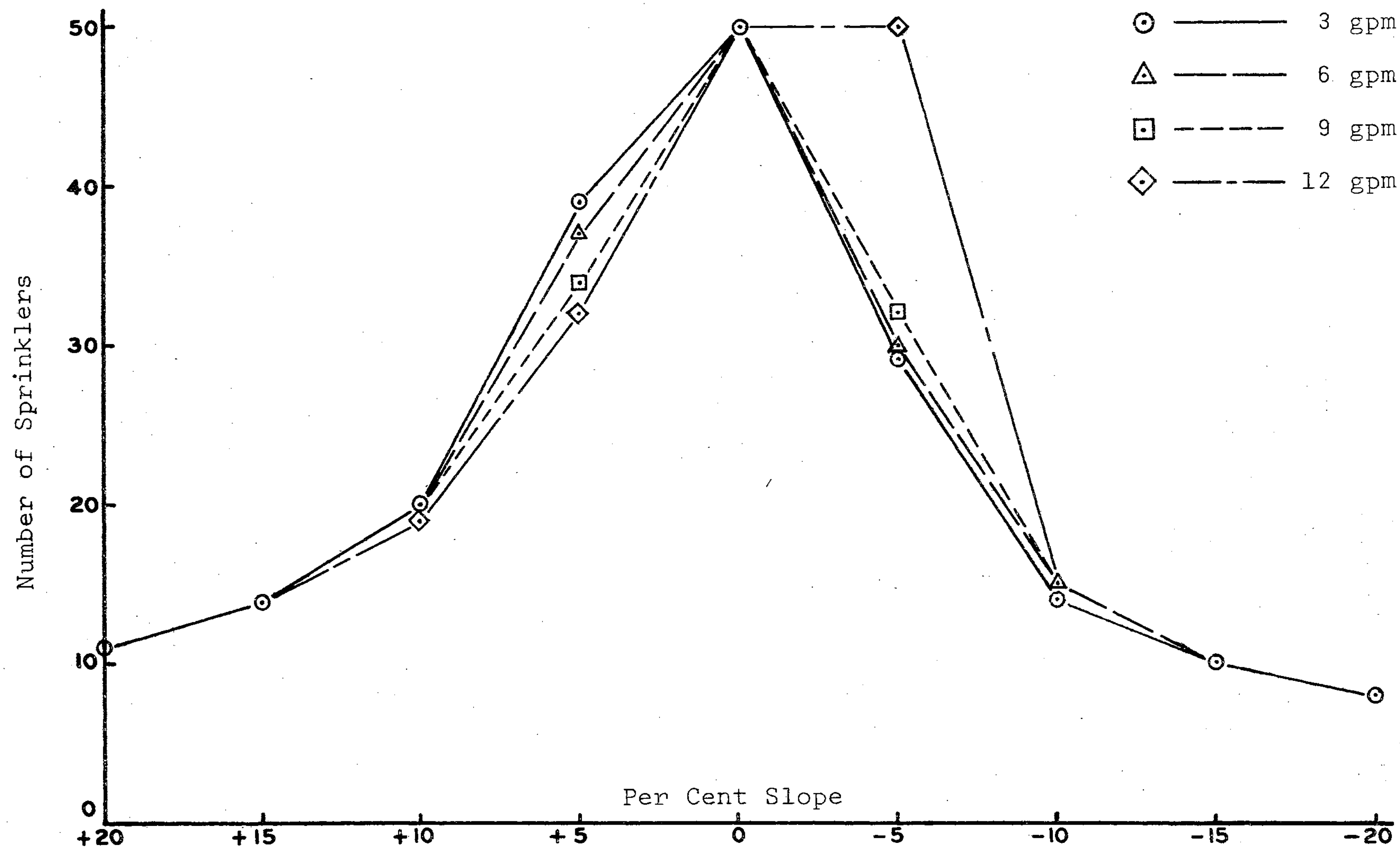

Figure 13. Effect of Slope on Maximum Number of Sprinklers For 5 inch Lateral

lateral without exceeding the allowable pressure variation. The study was limited to a maximum of 50 sprinklers per lateral.

The Effect of Slope on R_1 and R_2 Factors

The effect of slope on the values of R_1 and R_2 can probably be best shown by using an example. The general equation for estimating pressure at the main is:

$$P_m = P_a + R_1H_f + R_2H_e$$

where

P_a is the average sprinkler pressure

R_1 is the factor for friction loss

H_f is the actual friction loss occurring

R_2 is the factor for pressure change due to elevation, and

H_e is the pressure change due to elevation.

Assume a lateral of 40 sprinklers is on a +5 per cent slope, and the average sprinkler pressure to be 60 psi with an allowable pressure loss of 12 psi. Using the calculated values for R_1 and R_2 for a +5 per cent slope, with the first sprinkler 30 feet from the main:

$$P_m = 60 + .769(12) + .521(26) = 82.8 \text{ psi}$$

Using the most commonly used values of $R_1 = 0.75$ and $R_2 = 0.5$, the estimated pressure at the main would be

$$P_m = 60 + .75(12) + .5(26) = 82.0 \text{ psi}$$

The net difference between the two estimates being 0.8 psi.

If the first sprinkler is located 15 feet from the main instead of 30 feet, the estimated pressure at the main is:

$P_m = 60 + .75(12) + .511(25.65) = 82.1$ psi.

Again using the common values for R_1 and R_2,

$P_m = 60 + .75(12) + .50(25.65) = 81.8$ psi.

The net difference between the estimates being 0.3 psi.

Had the same lateral been on a -5 per cent slope, for the situation where the first sprinkler is 30 feet from the main:

$P_m = 60 + .761(12) - .523(26) = 55.5$ psi.

Using the commonly used values for R_1 and R_2,

$P_m = 60 + .75(12) - .5(26) = 56.0$ psi.

The net difference between the two estimates being 0.5 psi.

For the situation of the first sprinkler being 15 feet from the main,

$P_m = 60 + .749(12) - .513(25.65) = 55.8$ psi.

While for $R_1 = 0.75$ and $R_2 = 0.5$, the estimated pressure loss is

$P_m = 60 + .75(12) - .5(25.65) = 56.2$ psi.

Again the difference between the two estimates is only 0.4 psi.

All of these differences in pressure due to using calculated values versus the commonly used values of R_1 and R_2 are less than 1.0 psi, and are not appreciable from the standpoint of design.

Table VII gives values for R_1 and R_2 and the standard deviation of these values for laterals with greater than 5 sprinklers placed on various slopes, with the first sprinkler located 30 feet from the main line, regardless of lateral diameter or sprinkler discharge. Table VIII gives the same values for a lateral with the first sprinkler located 15 feet from the main line. Figure 14 shows the effect of slope on values of R_1 and R_2.

Tables IX and X show calculated values of R_1 and R_2 for laterals with the first sprinkler located 30 feet and 15 feet from the main line respectively. These values were calculated on the basis of sprinkler capacity, regardless of the lateral diameter or per cent slope. Figure 15 shows the effects of sprinkler capacity on values of R_1 and R_2.

Tables XI and XII show similar values of R_1 and R_2 where calculations were based on lateral diameter, regardless of sprinkler discharge or per cent slope. Figure 16 shows the effects of lateral diameter on values of R_1 and R_2.

TABLE VII

LEAST SQUARES VALUES OF R_1 AND R_2 FOR SPRINKLER LATERAL ON SLOPE WITH FIRST SPRINKLER 30 FEET FROM MAIN LINE AND MORE THAN 5 SPRINKLERS

Per Cent Slope	R_1	R_2	Standard Deviation
+20	0.757	0.558	0.249
+15	0.750	0.549	0.240
+10	0.763	0.537	0.206
+ 5	0.769	0.522	0.139
0	0.758	0.000	0.028
- 5	0.761	0.523	0.106
-10	0.774	0.540	0.174
-15	0.869	0.562	0.165
-20	0.858	0.571	0.150

Slopes are considered positive when the elevation increases from the main line to the last sprinkler.

TABLE VIII

LEAST SQUARES VALUES OF R_1 AND R_2 FOR SPRINKLER LATERAL ON SLOPE WITH FIRST SPRINKLER 15 FEET FROM MAIN LINE AND MORE THAN 5 SPRINKLERS

Per Cent Slope	R_1	R_2	Standard Deviation
+20	0.734	0.531	0.131
+15	0.733	0.527	0.125
+10	0.744	0.519	0.105
+ 5	0.750	0.511	0.067
0	0.747	0.000	0.009
− 5	0.749	0.513	0.057
−10	0.755	0.522	0.081
−15	0.800	0.533	0.088
−20	0.793	0.538	0.081

Slopes are considered positive when elevation increases from the main line to the last sprinkler.

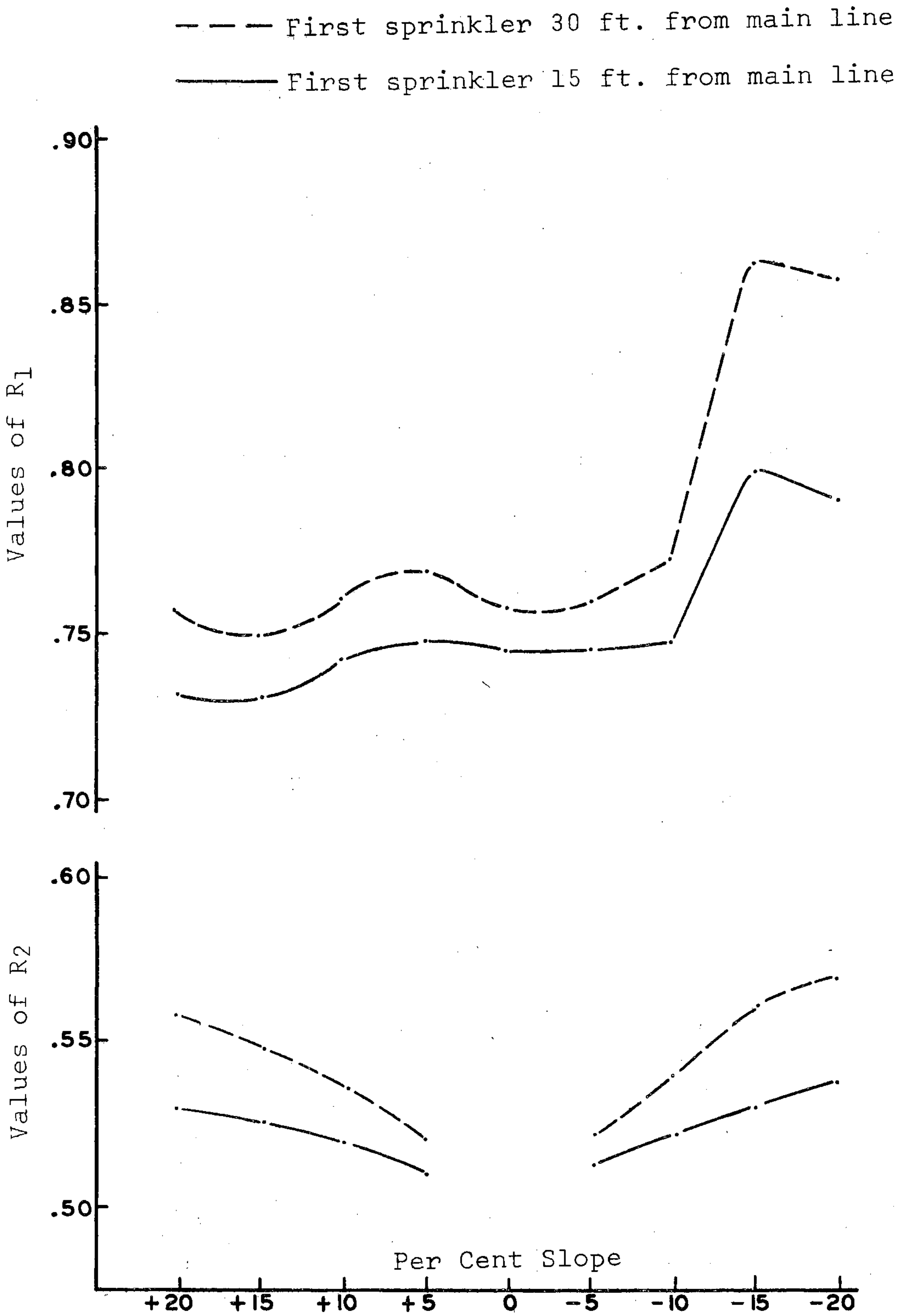

Figure 14. Effect of Slope on Values of R_1 and R_2

TABLE IX

LEAST SQUARES VALUES OF R_1 AND R_2 BASED ON SPRINKLER DISCHARGE REGARDLESS OF LATERAL DIAMETER OR SLOPE, FIRST SPRINKLER LOCATED 30 FEET FROM THE MAIN LINE

Sprinkler Discharge	R_1	R_2	Standard Deviation
3 gpm	0.755	0.536	0.248
6 gpm	0.767	0.537	0.241
9 gpm	0.771	0.537	0.236
12 gpm	0.771	0.538	0.242

TABLE X

LEAST SQUARES VALUES OF R_1 AND R_2 BASED ON SPRINKLER DISCHARGE REGARDLESS OF LATERAL DIAMETER OR SLOPE, FIRST SPRINKLER LOCATED 15 FEET FROM THE MAIN LINE

Sprinkler Discharge	R_1	R_2	Standard Deviation
3 gpm	0.746	0.519	0.128
6 gpm	0.752	0.519	0.123
9 gpm	0.752	0.520	0.476
12 gpm	0.753	0.520	0.122

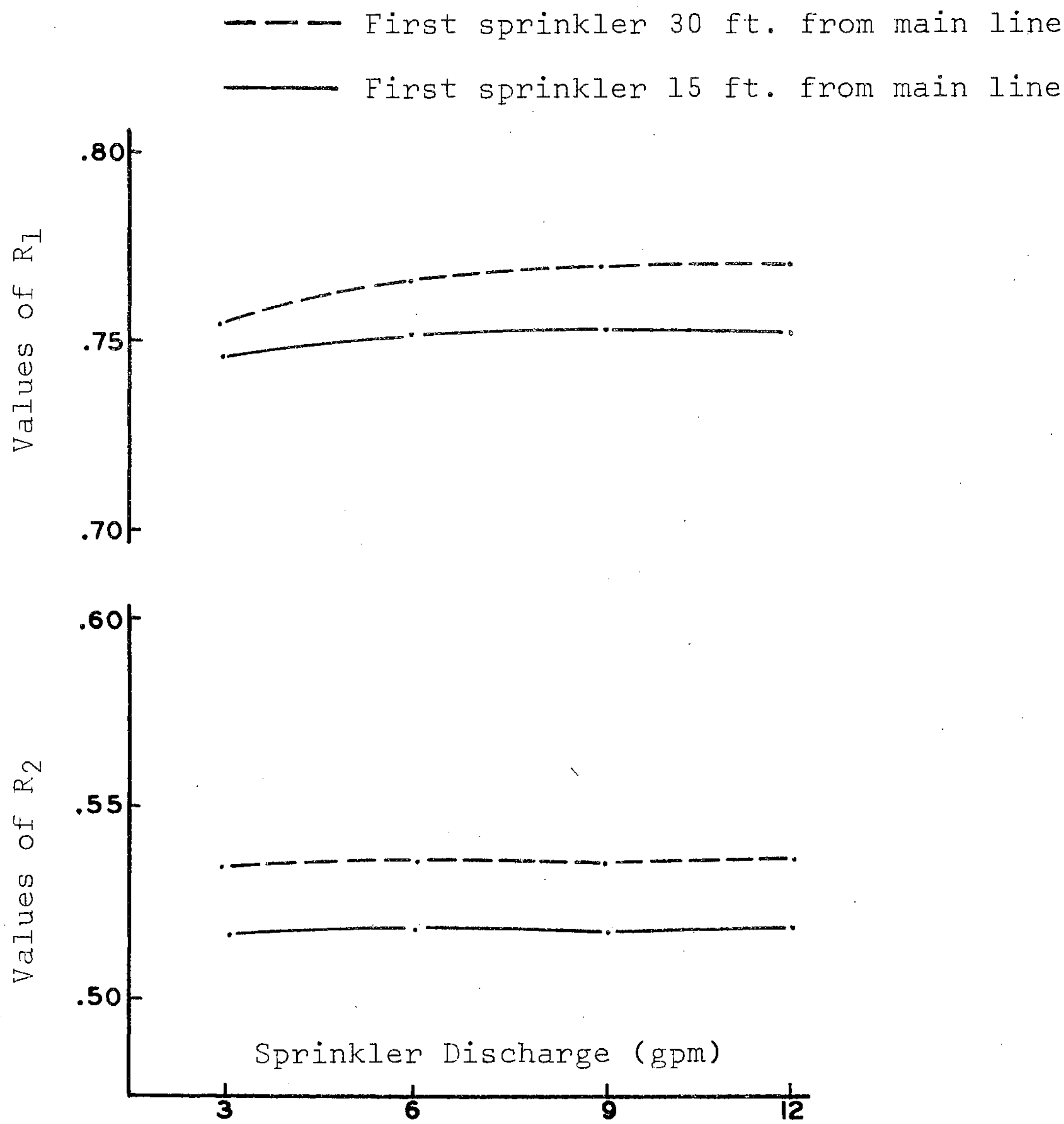

Figure 15. Effect of Sprinkler Discharge on Values of Factors R_1 and R_2

TABLE XI

LEAST SQUARES VALUES FOR R_1 AND R_2 BASED ON LATERAL DIAMETER REGARDLESS OF SPRINKLER DISCHARGE OR SLOPE, FIRST SPRINKLER LOCATED 30 FEET FROM THE MAIN LINE

Lateral Diameter	R_1	R_2	Standard Deviation
3 inch	0.772	0.540	0.225
4 inch	0.769	0.536	0.242
5 inch	0.767	0.535	0.254

TABLE XII

LEAST SQUARES VALUES FOR R_1 AND R_2 BASED ON LATERAL DIAMETER REGARDLESS OF SPRINKLER DISCHARGE OR SLOPE, FIRST SPRINKLER LOCATED 15 FEET FROM THE MAIN LINE

Lateral Diameter	R_1	R_2	Standard Deviation
3 inch	0.753	0.521	0.112
4 inch	0.752	0.519	0.122
5 inch	0.751	0.518	0.129

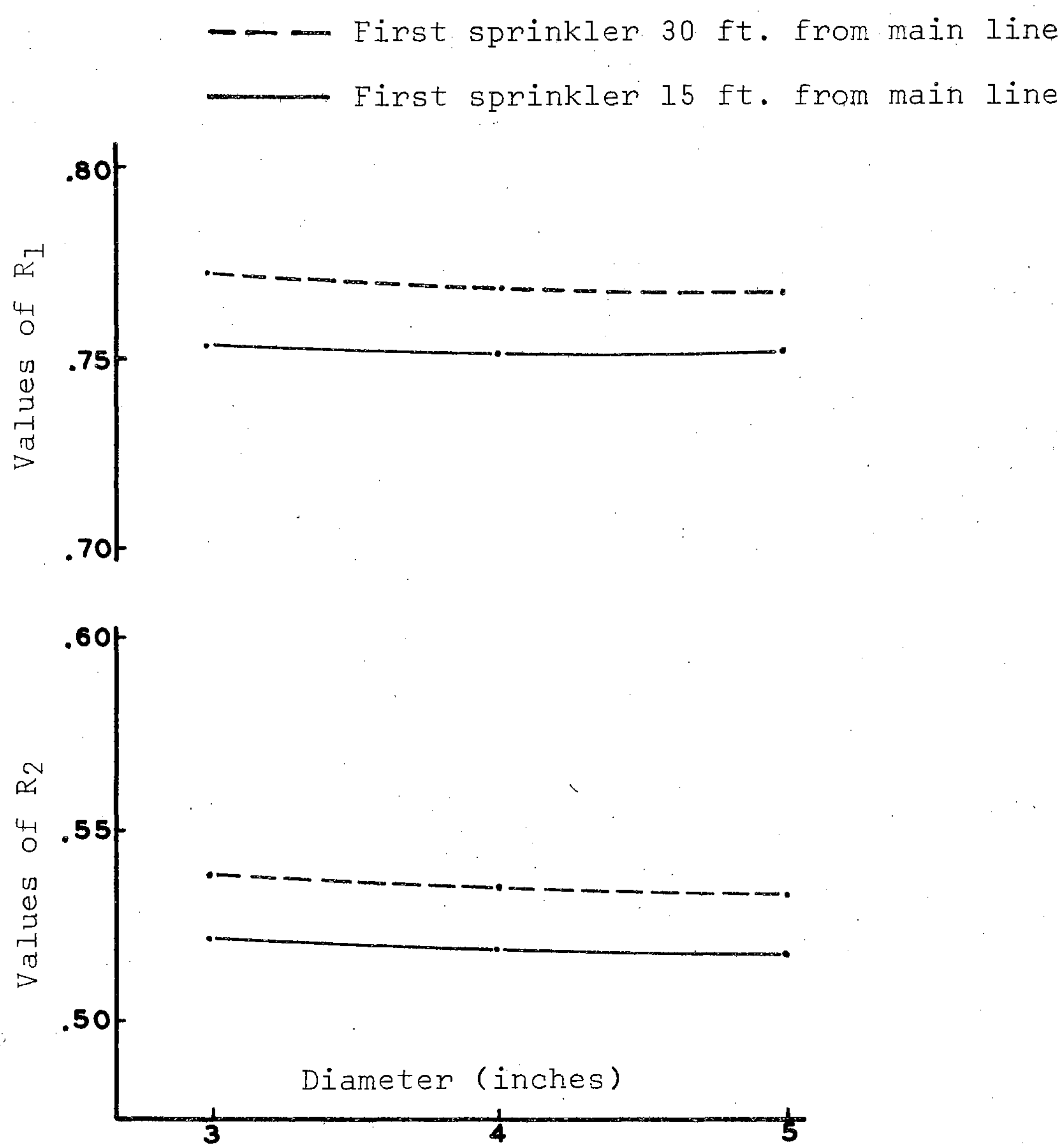

Figure 16. Effect of Lateral Diameter on Values of Factors R_1 and R_2

CHAPTER VI

SUMMARY AND CONCLUSIONS

An analytical study utilizing an electronic computer was made to determine the effect of varying sprinkler discharge and the effect of slope on values of F factors used for sprinkler lateral design. Also included in the study was an investigation of the effect of slope on the factors R_1 and R_2 by which the actual friction loss in the lateral and the pressure change due to elevation are respectively multiplied in estimating the pressure at the main line.

The following conclusions were made, based on the results of the study.

1. The effect of varying sprinkler discharge and the effect of slope on values of the F factor are measureable.
2. Improved values of F were determined in this study.
3. In typical sprinkler design situations, the use of these improved values of F does not result in estimates having a practical difference from those estimates obtained using F values proposed by Christiansen and Jensen and Fratini.
4. Slope is the dominating factor in limiting the

number of sprinklers permissible on a lateral on slopes greater than ±15 per cent.

5. Improved values for R_1 and R_2 were determined in the study.

6. In typical design situations, using these improved values for R_1 and R_2 does not result in appreciably different solutions from those arrived at using the commonly accepted values of $R_1 = 0.75$ and $R_2 = 0.50$.

7. Further studies are not recommended.

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4. Ree, W. O. "Head Loss in Quick-Coupled Aluminum Pipe." United States Department of Agriculture, Agriculture Handbook No. 147, 1959.

5. Wiersma, John L. "Effect of Wind Variation on Water Distribution from Rotating Sprinklers." South Dakota Agricultural Experiment Station, Technical Bulletin No. 16, 1955.

6. Natrella, Mary G. "Polynomial and Multivariable Relationships." Experimental Statistics, National Bureau of Standards Handbook No. 91, 1963.

APPENDIX

```
10      READ 100, A, DIA, SK
        PUNCH 300
        S=25.
1       P=60
        Q2=0.
        PT=0.
        G=0.
        HLT=0.
        S=S-5.
        DSLO-SQR(10000.+S*S)
2       DELEV=(30./DSLO)*S
        PELEV =DELEV/2.31
        G=G+1
        Q1=A*SQR(P)
        Q2=Q2+Q1
        AREA=.7854*(DIA**2)
        V=(Q2*.002228)/AREA
        HL=SK*(V**1.9)/((2.31*1000.)*DIA**1.1))
        DELHL=HL*30
        PT=PT+P
        PA=PT/G
        DELP=DELHL+PELEV
        PM=P+DELP
        P=P+DELP
        DIST=(G*30.)
        HLT=PM-60.-(((DIST/DSLO)*S)/2.31)
        HLF=HL*DIST
        F=HLT/HLF
        PUNCH 6,G,DIST,Q1,PM,PA,F,S
        IF(P+42) 5,5,7
7       IF(G-50.) 8,5,5
8       IF(P-85.7) 2,5,5
5       IF(S+20.) 9,9,1
9       CONTINUE
        GO TO 10
6       FORMAT (F5.1,F9.1,F9.3,F7.1,F9.3,F11.6,F7.1)
100     FORMAT (f10.7,F10.6,F10.3)
300     FORMAT (4H  NO,7X,1HD,7X,3HGPM,5X,1HP,6X,2HAP,9X,1HS)
        END
```

Figure 2

FORTRAN PROGRAM FOR CALCULATING FRICTION FACTORS IN SPRINKLER LATERALS WITH FIRST SPRINKLER LOCATED 30 FEET FROM MAINLINE

```
10      READ 100, A,DIA,SK
        PUNCH 300
        S=25
1       P=60
        Q2=0.
        PT=0.
        G=0.
        HLT=0.
        S=S-5.
        DSLO=SQR(10000+S*S)
2       DELEV=(30./DSLO)*S
        PELEV=DELEV/2.31
        G=G+1
        Q1=A*SQR(P)
        Q2=Q2+Q1
        AREA=.7854*(DIA**2)
        V=(Q2*.002228)/AREA
        HL=SK*(V**1.9)/((2.31*1000.)*(DIA**1.1))
        DELHL=HL*30.
        PT=PT+P
        PA=PT/G
        DELP=DELHL+PELEV
        PM=P+.5*DELP
        P=P+DELP
        DIST=(G*30.)-15.
        HLT=PM-60.-(((DIST/DSLO)*S)/2.31)
        HLF=HL*DIST
        F=HLT/HLF
        PUNCH 6,G,DIST,Q1,PM,PA,F,S
        IF(P+42.) 5,5,7
7       IF(G-50.) 8,5,5
8       IF(P-85.7) 2,5,5
5       IF(S+20.) 9,9,1
9       CONTINUE
        PUNCH 400
        PUNCH 500
        GO TO 10
6       FORMAT (F5.1,F9.1,F9.3,F7.1,F9.3,F11.6,F7.1)
100     FORMAT (F10.7,F10.6,F10.3)
300     FORMAT (4H  NO,7X,1HD,7X,3HGPM,5X,1HP,6X,1HAP,9X,1HS)
        END
```

Figure 3

FORTRAN PROGRAM FOR CALCULATING FRICTION FACTORS IN SPRINKLER LATERALS WITH FIRST SPRINKLER LOCATED 15 FEET FROM MAINLINE

```
10      READ,A,DIA,SK
        S=25.
1       P=60.
        Q2=0.
        PT=0.
        G=0.
        HLT=0.
        S=S-5.
        DSLO=SQR(10000.+S*S)
2       DELEV=(30./DSLO)*S
        PELEV=DELEV/2.31
        G=G+1.
        Q1=A*SQR(P)
        Q2=Q2+Q1
        AREA=.7854*(DIA**2)
        V=(Q2*.002228)/AREA
        HL=SK*(V**1.9)/((2.31*1000)*(DIA**1.1))
        DELHL=HL*30.
        PT=PT+P
        PA=PT/G
        DELP=DELHL+PELEV
        PM=P+DELP
        P=P+DELP
        DIST=(G*30.)
        PLSLO=(((DIST/DSLO)*S)/2.31)
        HLT=PM-60.-PLSLO
        HLF=HL*DIST
        F=HLT/HLF
        Y=PM-PA
        PUNCH,Y,HLT,PLSLO
        IF(P-42.) 5,5,7
7       IF(G-50.) 8,5,5
8       IF(P-85.7) 2,5,5
5       IF (S+20) 9,9,1
9       CONTINUE
        GO TO 10
        END
```

Figure 4

FORTRAN PROGRAM FOR CALCULATING VALUES USED TO DETERMINE R FACTORS IN SPRINKLER LATERALS WITH FIRST SPRINKLER LOCATED 30 FEET FROM MAIN LINE

```
10      READ,A,DIA,SK
        S=25.
1       P=60.
        Q2=0.
        PT=0.
        G=0.
        HLT=0.
        S=S-5
        DSLO=SQR(10000.+S*S)
2       DELEV=(30./DSLO)*S
        PELEV=DELEV/2.31
        G=G+1.
        Q1=A*SQR(P)
        Q2=Q2+Q1
        AREA=.7854*(DIA**2)
        V=(Q2*.002228)/AREA
        HL=SK*(V**1.9)/((2.31*1000)*(DIA**1.1))
        DELHL=HL*30.
        PT=PT+P
        PA=PT/G
        DELP=DELHL+PELEV
        PM=P+.5*DELP
        P=P+DELP
        DIST=(G*30.)-15.
        PLSLO=(((DIST/DSLO)*S)/2.31)
        HLT=PM-60.-PLSLO
        HLF=HL*DIST
        F=HLT/HLF
        Y=PM-PA
        PUNCH,Y,HLT,PLSLO
        IF(P-42.) 5,5,7
7       IF(G-50.) 8,5,5
8       IF(P-85.7) 2,5,5
5       IF(S+20.) 9,9,1
9       CONTINUE
        GO TO 10
        END
```

Figure 5

FORTRAN PROGRAM FOR CALCULATING VALUES USED TO DETERMINE R FACTORS IN SPRINKLER LATERALS WITH FIRST SPRINKLER LOCATED 15 FEET FROM MAIN LINE

```
1     READ,N
      SX1Y=0.
      SX2Y=0.
      SX1X2=0.
      SX1SQ=0.
      SX2SQ=0.
      SRSQ=0.
      DO 5 I=1,N
      READ,Y,X1,X2
      SX1Y=SX1Y+X1*Y
      SX2Y=SX2Y+X2*Y
      SX1X2=SX1X2+X1*X2
      SX1SQ=SX1SQ+X1**2
5     SX2SQ=SX1SQ+X2**2
      IF(SX2SQ) 20,20,30
20    R2=0.
      R1=SX1Y/SX1SQ
      GO TO 40
30    TOP=(SX1Y-(SX2Y*(SX1SQ/SX1X2)))
      BOT=(SX1X2-(SX2SQ*(SX1SQ/SX1X2)))
      R2=TOP/BOT
      R1=(SX1Y-(R1*SX1X2))/(SX1SQ)
40    PUNCH,R1,R2
      GO TO 1
      END
```

Figure 6

FORTRAN PROGRAM FOR CALCULATING R_1 AND R_2 FACTORS FOR SPRINKLER LATERALS

```
1       READ,R1,R2
        READ,N
        SRSQ=0.
        DO 70 I=1,N
        READ,Y,X1,X2
        YCAL=R1*X1+R2*X2
        R=Y-YCAL
70      SRSQ=SRSQ+R**2
        C=N
        VAR=(1./(C-2.))*SRSQ
        STDEV=SRQ(VAR)
        PUNCH,R1,R2,STDEV
        GO TO 1
        END
```

Figure 7

FORTRAN PROGRAM FOR CALCULATING STANDARD DEVIATION OF R1 AND R2 FACTORS FOR SPRINKLER LATERALS

VITA

Delbert Preston Schwab

Candidate for the Degree of

Master of Science

Thesis: THE EFFECT OF SLOPE AND VARYING SPRINKLER DISCHARGE ON F FACTORS FOR SPRINKLER LATERAL DESIGN

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