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10. Abstract
A method was suggested and demonstrated for predicting the field performance of sprinklers operated in unsteady wind conditions from a limited number of single sprinkler tests and a limited amount of wind data. The usefulness of a single sprinkler test is increased by rotating it to any angle, thus enabling it to depict the effects of wind from any direction and resulting in a reduction of the number of tests needed. Wind data is grouped into 45 angle segments and averaged within five mile per hour wind speed intervals. The method involves synthesizing the effects of unsteady wind on sprinkler water distribution by utilizing a computer to stack a series of sprinkler tests conducted in steady wind. The resulting total stacked test pattern representing the influence of unsteady wind is utilized for predicting the uniformity of water distribution for a sprinkler operated in the wind conditions modeled.

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SPRINKLER PERFORMANCE PREDICTION
WHEN OPERATED IN UNSTEADY WIND

by

Thomas J. Young

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Agricultural and Irrigation Engineering

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The information and conlusions in this report do not necessarily reflect the position of USAID or the United States Government.

Thomas J. Young

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Sprinkler Performance Prediction When
Operated in Unsteady Wind
by
Thomas J. Young, Master of Science
Utah State University, 1973

Major Professor and Thesis Director: Dr. Jack Keller
Department: Agricultural and Irrigation Engineering

A method was suggested and demonstrated for predicting the field performance of sprinklers operated in unsteady wind conditions from a limited number of single sprinkler tests and a limited amount of wind data. The usefulness of a single sprinkler test is increased by rotating it to any angle, thus enabling it to depict the effects of wind from any direction and resulting in a reduction of the number of tests needed. Wind data is grouped into 45° angle segments and averaged within five mile per hour wind speed intervals.

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(95 pages)

INTRODUCTION

The use of sprinklers to apply irrigation water is a popular irrigation practice. Interest in using sprinkler irrigation systems continues to grow as the efficient use of water becomes more important for profitable crop production. An efficient irrigation system must be capable of applying the water where and when it is needed in order to maximize crop yield and quality.

The evenness of water application over a crop area is defined as distribution uniformity. It is an important aspect of sprinkler system design which should be known in advance. Researchers have conducted many investigations to determine the uniformity of distribution. Results indicate it to be affected by many factors (Redditt, 1965). They are as follows:

(1) wind speed
(2) wind direction
(3) spray loss
(4) spacing
(5) riser height
(6) sprinkler head design
(7) pressure
(8) set time

Uniformity can be improved by proper selection of the controllable factors. Of the above list, spacing, riser height, sprinkler head design, pressure, and set time are controllable aspects of a sprinkler irrigation system and can be selected to produce uniform water distribution in no wind conditions. Spray losses can be partially controlled by proper nozzle design and use of correct pressure.

The effect of wind speed and direction on uniformity has been studied using constant winds. Moynahan (1972) presented a method for a variety of steady state winds. Branscheid and Hart (1968) have done work on predicting uniformity by superimposition. However, sprinklers operated in environmental conditions are subject to winds variable in speed and direction. At present, no reliable method exists for predicting the field performance of a sprinkler system that is to be operated in variable wind conditions.

Objectives

The objectives of this research are to answer the following questions:

Can a practical procedure be developed where standard test site sprinkler performance data and wind direction-speed profiles are used to synthesize field performance of sprinklers operated under variable wind conditions?

What effect does unsteady wind direction or speed have on sprinkler water distribution uniformity as compared to performance in steady winds?

Can the shift in center of mass of the can catch data of a single sprinkler provide a useful single parameter to define an unsteady wind? If center of mass is not sufficient, can another parameter be found?

It is hoped that understanding the effect variable wind has on sprinkler performance may lead to improving uniformity with better designs and selective management practices.

REVIEW OF LITERATURE

Analysis of Sprinkler Distribution Uniformity

A uniformly distributing sprinkler system would apply the same depth of water over the entire area irrigated. A system supplying a perfectly uniform distribution could be operated to apply the exact amount of water needed by the crop. This situation can never be fully achieved, however, because some of the factors affecting distribution uniformity cannot be controlled. Investigations have been made to determine which factors affect distribution uniformity. Conclusions indicate they can be grouped into the categories of design factors, environmental conditions, and management practices.

Design factors

Certain elements of a sprinkling system are variable but once a selection for the system design has been made, they become constant. These elements have an effect on distribution and will be considered as follows: physical sprinkler design, nozzle size, rate and uniformity of rotation, riser height, and spacing along and between laterals (constant for solid set systems).

Physical sprinkler design. Investigations have been made to determine the effect of sprinkler head design on uniformity. Seginer (1963) found differences in oscillating arm length and nozzle shape and length caused slight differences in distribution characteristics. These differences were found to be small from a practical point of view. Results from studies such as Wiersma (1950) have shown uniformity in wind conditions is affected by the angle between the nozzle and horizontal. A low trajectory of 21° is generally accepted to provide maximum wind resistance and uniform coverage. Also, a single nozzle usually gives better uniformity in winds above eight miles per hour than a sprinkler head equipped with two nozzles.

Nozzle size. For any specific spacing the larger nozzle sizes have higher distribution uniformity for any given operating pressure and sprinkler head. An increase in nozzle diameter tends to produce larger drops which are influenced less by wind than smaller drops (Wiersma, 1950). Also, Bilanski and Kidder (1958) found as the nozzle size is increased, the nozzle approaches a tube which gives a more desirable distribution than a tapered nozzle.

Rate and uniformity of rotation. The sprinkler head of most interest in irrigation system design is the oscillating arm or impact type. The head rotates through a small angle each time the spring-loaded arm strikes the sprinkler body. Christiansen (1941) reported the high rate and nonuniformity of sprinkler head rotation were the major factors causing poor distribution uniformity. Recent advances in spring and bearing materials have significantly improved the uniformity of rotation until it no longer stands as a major problem. The rate of rotation influences the diameter covered by the sprinkler. Bilanski and Kidder (1958) observed an increase in rate of rotation was accompanied by a decrease in distance the water traveled. Water drop size is smaller for faster rotation resulting in greater wind influence and generally lower uniformity.

Riser height. Investigators such as Wiersma (1950) and Hart (1959) report riser height above the crop to be insignificant at wind speeds less than four miles per hour. However, in winds of higher speeds riser height has an influence on uniformity. Wiersma (1950) found a greater difference in uniformity between 6 inch and 12 inch risers than between 24 inch and 48 inch risers. Air turbulence near the crop surface distorts the sprinkler pattern more than steady air flow which occurs at increased riser heights (Keller et al., 1967). Hart (1959) concluded from his investigations that water losses resulting from wind drift increased as riser height increased.

Spacing along and between laterals. Distribution uniformity generally decreases as the spacing is increased. The effect of wind on water distribution is more pronounced as the spacing between laterals increases (Seginer, 1969). It is possible to have a spacing where the points of heavy application for one sprinkler fill in points of light application from an adjacent sprinkler. This spacing would result in the best uniformity. Alternate spacing of sprinklers on the lateral is one attempt to achieve this best uniformity when the wind pattern is similar in speed and direction from irrigation to irrigation.

Environmental conditions

The environmental conditions during the time of sprinkler system operation have an important effect upon the uniformity of water distribution. In the system design attention must be given to wind speed and direction, wind histories, and water losses.

Wind speed and direction. Certain conclusions about the effect of wind speed and direction can be drawn from research such as that done by Christiansen (1941), Allison and Hesse (1969), and Seginer

(1969). It is known the uniformity of distribution test patterns gets worse the higher the wind speed and also, the effect of wind speed is small at very close sprinkler spacings.

Lower uniformity of water distribution at high wind speeds is primarily the result of quicker breakup of the jet. This produces a shorter cross wind range from the nozzle of the sprinkler. The jet range reduction on the upwind side is usually matched by a corresponding range increase downwind of the sprinkler. This causes a high concentration of water near the sprinkler on the upwind side and a deficiency on the downwind side. The result is lower uniformity (Redditt, 1965).

Christiansen (1941) concludes from his research that the effect of wind on the distribution uniformity over a large area can largely be overcome by proper spacing of the sprinkler. Closely spaced sprinklers provide adequate overlap which makes unevenness less serious because the local areas of high and low concentration always occur at the same relative position with respect to the sprinklers and do not overlap on themselves to produce an exaggerated effect (Christiansen, 1941, p. 85). This conclusion is justified only in areas where the winds occur in patterns and the sprinklers are moved after each operation.

The amount of variability in wind velocity (both speed and direction) has an important effect on the distribution of water, especially with solid set systems. If the wind velocity changes, an area which received a heavy application one time might get a light application the next. Usually the greater the wind variation the more smoothing effect there is (Redditt, 1965).

Efforts have been made to use the direction of the prevailing wind as a basis for system lateral layout selection. Seginer (1969) and Keller et al. (1967) recommended the lateral be placed perpendicular to the wind direction. Hart (1959) concluded from his research that when laterals are parallel to the wind a greater uniformity results than when the wind angle is perpendicular to the lateral direction. Wiersma (1950) and Ptacek (1972) performed studies which revealed there is no single wind orientation which provides a superior uniformity for all sprinkler spacings and wind conditions. In practical field design the common practice is to place the laterals at right angles to the prevailing wind.

Wind speed and direction affect the sprinkler spacings that can be used without loss of uniformity. It is a general practice for the maximum spacing under no wind conditions to not exceed 70 percent of the diameter of coverage for one sprinkler. The higher the average wind condition, the nearer the spacing should approach 30 percent of the diameter. For winds above eight miles per hour the spacing should remain at 30 percent (Fry, 1969).

Moynahan (1972) made a study of wind effects on sprinkler performance in which he used the shift in center of mass as an indication of wind direction and sprinkler stability in wind. He proposed the location of the center of mass of the can catch data on a plane parallel to the soil surface depicts the average wind effect on a single sprinkler pattern test. The center of mass of a single sprinkler pattern is defined as the point where the moment of the can catch values (weighted by the distance from the sprinkler head) sum to zero. It can be visualized as the balancing point for the mass of water emitted from a sprinkler during a test. For the concept to be valid the sprinkler head must rotate uniformly to position the center of mass (C_m) at the sprinkler in zero wind conditions. Any wind would move C_m away from the sprinkler opposite the direction from which the wind was blowing. Moynahan (1972) realized it would be possible to have high wind speeds with direction vectors shifting in such a way that the center of mass remained at the sprinkler. However, by confining his work to winds with essentially constant directions he avoided the no shift situation.

Wind histories. An unsteady wind may be classified into three general categories: constant speed--variable direction, variable speed--constant direction, and variable speed--variable direction. The third case (variable speed and direction) is the most difficult to characterize. The following discussion is concerned with an unsteady wind variable in speed and direction. Wind histories give the variation of wind speed and direction with time during a sprinkler operation period. Analysis of the wind histories can give insight into proper management practices and aid in making better system designs.

Seginer (1969) made a comprehensive study in which he considered the effect wind variation had on uniformity. He found the use of one sprinkler pattern to predict field performance in wind may be satisfactory for solid set systems; however, a significant error may arise when the single sprinkler pattern concept is applied to a system where laterals are moved and then subjected to different wind conditions. The direction of lateral movement as related to prevailing wind direction can result in either convergence or divergence of water distribution patterns. The effect of convergence is an increase in the average depth of irrigation between two positions of a lateral. This comes as a result of a reversal in wind direction such that the area between two adjacent lateral positions is always downwind. Divergence results if the intermediate area is consistently upwind. Divergence produces the effect of a decrease in depth of irrigation. Branscheid and Hart (1968) found wind histories must be considered when predicting field system distribution from a single sprinkler pattern. Analysis has shown that performance of a solid set system can be predicted by a single sprinkler pattern subject to one wind history. However, predicting the performance of a portable system requires a combination of several single sprinkler patterns each having a different wind history (Branscheid and Hart, 1968).

Allison and Hesse (1969) used wind histories in a portion of their investigation of wind effects on sprinkler performance. Although this study was more concerned with sprinkling operation practices, it also led to the conclusion the effect on sprinkler performance in wind conditions could be simulated if adequate wind data (wind histories) were available. Wind effects were simulated by overlapping sprinkler tests conducted in various steady winds. The sequence of overlapping patterns was determined by the wind history they modeled.

Water losses. The loss of water due to spray evaporation and wind drift are of specific concern in sprinkler irrigation. Frost and Schwalen (1960) studied losses from spray evaporation and drift. A correlation between spray losses and vapor pressure deficit was found. The losses were found to be approximately proportional to nozzle pressure and wind speed and inversely proportional to nozzle diameter. Kraus (1966) made a comprehensive study which revealed total water application losses ranged from 3.4 to 17.0 percent with an average of 36 percent of these total losses due to wind drift.

Drift losses may be considered negligible for low wind velocities. However, an increase in wind speed combined with an increase in sprinkler riser height can cause significant water losses (Hart, 1959). Sternberg (1967) has made an analysis of sprinkler irrigation losses including an evaluation of day versus night sprinkling. He concluded daytime and nighttime sprinkler irrigation have similar losses under low wind velocities.

Management practices

Sprinkler systems may be properly managed to produce a significant increase in distribution uniformity. Preferred management practices are likely to improve uniformity if consideration is given to time of operation, direction of lateral movement and use of alternate sets.

Allison and Hesse (1969) conducted a study to evaluate the effect of selective sprinkler operation on distribution uniformity for a portable system. A comparison of uniformity was made between operations where sprinkling was stopped for six hours daily during high winds and operations where sprinkling was continuous throughout the entire season. They observed the average overall water distribution uniformities obtained from both operations were not significantly different. They concluded the additional costs and operational problems created by sprinkling system shut down during high winds could not be justified on the basis of increased uniformity.

Many areas are known to experience cyclic winds where a definite wind pattern is repeated once daily. This is common in coastal areas where the sea breeze-land breeze effect can completely reverse the wind direction from day to night. If the wind history at a particular field was carefully characterized, successive irrigations could be scheduled at different times of the day so different wind conditions prevailed. Each individual application would have its own uniformity, but an improved seasonal uniformity could be expected as the stacking of different patterns usually results in a better uniformity than any of the individual patterns (Redditt, 1965). This management practice is especially applicable to a solid set system.

Seginer (1969) made extensive tests which revealed the direction of lateral movement can have a significant effect on distribution of water from sprinklers subject to wind variations. A more even application of water may be obtained if wind changes, which may cause convergence or divergence of the distribution patterns, are considered when selecting operation practices. Keller et al. (1967) suggests alternate sets (staggered spacing) to smooth out variations in uniformity between two irrigations in order to improve the overall seasonal uniformity. This management technique can be applied to portable and mechanical move systems.

Methods of Characterizing Distribution Uniformity

The evenness with which water is applied over the area covered by sprinklers is defined as the distribution uniformity. A perfectly uniform application of water would require an equal depth be received by all the area being irrigated. This situation never exists in the field because of the factors previously listed. Additionally, sprinklers distribute water in circular patterns which by necessity must overlap on each other resulting in nonuniform application depths.

Christiansen (1942) felt it essential to compare sprinkler patterns and to determine how various spacings affect the resulting distribution of water. To do this, a numerical expression was needed to serve as an index of the uniformity. For this purpose the following expression for the uniformity coefficient (UC) was adopted,

$$UC = 100\ (1 - \frac{\Sigma x}{mn}) \qquad (1)$$

in which x is the deviation of individual observations from the mean value m, and n is the number of observations. It is apparent an absolutely uniform application would have a uniformity coefficient of 100 percent, and that a less uniform application would result in a lower percentage.

Wilcox and Swailes (1947), noting that Christiansen's uniformity coefficient gave no added weight to extreme values, proposed the following coefficient,

$$U = 100\ (1 - \frac{s}{\bar{x}}) \qquad (2)$$

where s is the standard deviation of the readings and $\bar{x}$ is the mean of the readings.

Benami and Hore (1964) developed a coefficient based on consideration of the deviation of readings from the means of the group of readings above and below the general mean. Their coefficient was the following:

$$A = \frac{C_1}{C_2} \tag{3}$$

where

$$C_1 = M_a - \frac{\Sigma|x|_a}{N_a} \tag{4}$$

$$C_2 = M_b - \frac{\Sigma|x|_b}{N_b} \tag{5}$$

where M_a is the mean of the group of readings above the general mean, M_b is the mean of the group of readings below the general mean, N_a and N_b are the number of readings above and below the mean, and $|x|_a$ and $|x|_b$ are the absolute deviation from M_a and M_b respectively. This coefficient reflects the influence of large deviations below the mean.

Extensive work has been done by Wilcox and McDougald (1955), Dabbous (1962), and Beale and Howell (1966) to evaluate and compare the relationships of sprinkler uniformity measures in attempts to find better indexes. Conclusions indicate regression lines relating measures of uniformity coefficients can be approximated quite well by line equations derived as if precipitation were normally distributed.

Hart (1961) realized in conjunction with evaluating the distribution uniformity, it was important to compute the cost of wasting water in the areas of excess and the cost of losing yield in the deficit areas. He observed the distribution patterns variation could be depicted by a Gaussian or normal distribution curve. Assuming a normal curve the following equation for uniformity coefficient was developed:

$$UC_H = 100 \left(1 - 0.798 \frac{s}{\bar{x}}\right) \qquad (6)$$

where s is the standard deviation and $\bar{x}$ is the mean application. With this equation, the uniformity coefficient was shown to have a physical interpretation useful in predicting the performance of a sprinkler system. Using a table of solutions of the equation for the required range of UC_H values simplifies the operation. For any specified UC_H value and mean application depth, the table can be entered to find the depth of water equaled or exceeded over various percents of the irrigated area. The Hart and Reynolds (1965) approach lent itself to development of relationships between water distribution, water availability, and water storage efficiency. These relationships are presented in tabular form in the above referenced literature.

Allison and Hesse (1969) made use of Hart's equation in developing a graphical relationship between coefficient of uniformity and effective use of water. For any particular percent of area to be adequately irrigated, and any coefficient of uniformity, the fraction of the applied water effectively used could be found. It was concluded the effectively used water taken as a percentage of the nominal application depth would be a measure of the overall efficiency of water use.

Predicting Distribution Uniformity from Sprinkler Tests

The value of sprinkler tests is they give an indication of the distribution of water which can be expected to occur in field operation. It is important to have advanced knowledge of the water distribution uniformity in producing effective sprinkler system designs.

Three main types of sprinkler tests are used in finding uniformity to predict field performance. All methods involve measuring the volume of water intercepted in equally spaced catch cans. The three test methods are the following:

(1) Simultaneously operated sprinkler test. The test area lies between four sprinklers situated at the corners. All sprinkler heads which would contribute to the test area are operated simultaneously. The uniformity calculated from the can catch results is good only for the particular spacing tested.

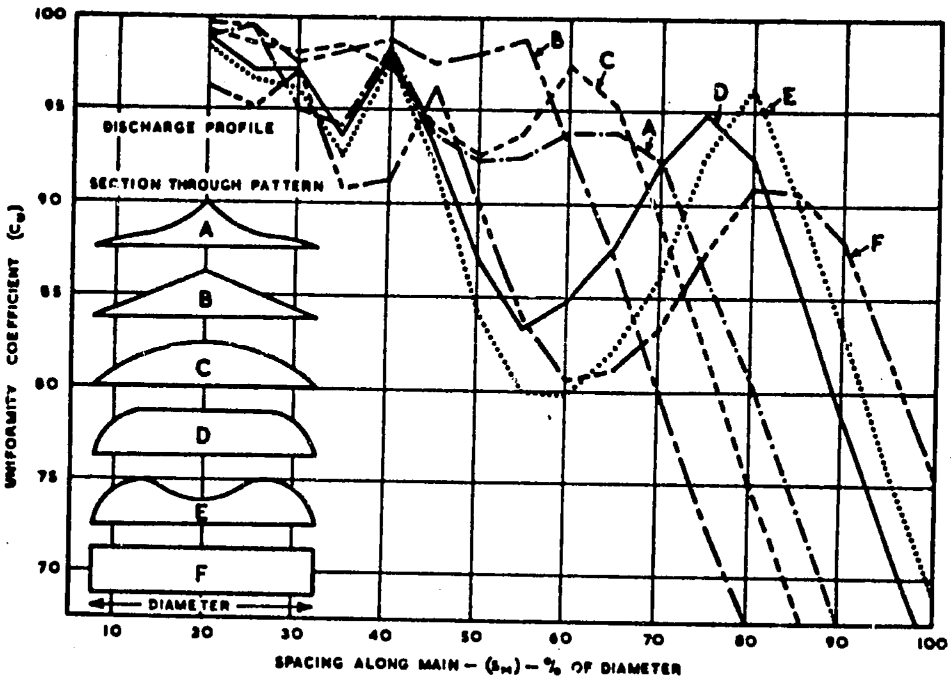
(2) The single sprinkler lateral test. The entire lateral with the sprinklers spaced along the line at the desired distance is operated. The test area is parallel to the lateral between two adjacent sprinklers. The can catch measurements must be summed with corresponding measurements from an adjacent lateral. This is accomplished by assuming the adjacent lateral would perform the same as the test lateral and then superimposing the can catch pattern upon itself offset by the amount of lateral spacing. This test is useful for simulating any lateral spacing with spacing along the lateral remaining constant.

(3) The single sprinkler test. One sprinkler is operated and measurements of application representing the total area receiving water are made. The resulting pattern is assumed to represent the pattern that would be obtained from each sprinkler in the field. By a process of superimposition the pattern is overlapped upon itself to give a distribution pattern between four adjacent sprinkler positions typifying the overall water application. Branscheid and Hart (1968) conducted research to compare test results of the overlapped

single sprinkler pattern and the single sprinkler lateral pattern. They concluded the overlapping process produced reliable results. The single sprinkler test is the most versatile, i.e., any spacing can be simulated by overlapping at the desired distances.

Christiansen (1941) realized the necessity of a simple method to predict sprinkler performance at various spacings. He approached the problem using the geometric sprinkler profile which is a plot of distance from the sprinkler versus depth of application. The concept he presented became very popular because it eliminated much of the tedious work in making a good spacing selection.

Christiansen worked with six basic sprinkler geometric profiles as shown in Figure 1. The coefficients of uniformity for each of the



SPACING ON LATERAL (S_L) = 5 % OF DIAMETER

DIAMETER = DIAMETER OF CIRCULAR AREA COVERED BY SPRINKLER DISCHARGE.

Figure 1. Christiansen's basic UC curves.

profiles was given by the dimensionless curves plotted against spacing along the main. The curves, as shown in Figure 1, were developed using a spacing of 5 percent of the diameter covered along the lateral line.

Strong (1961) presented a method to increase the usefulness of Christiansen's graph. It was essential to determine the proper spacing both on the lateral S_1 and on the main S_m. The theoretical uniformity coefficient (UC) was obtained by dividing 100 into the product of the UC values obtained from Figure 1 for both S_1 and S_m. This method was tested by comparing results with those found through overlapping sprinkler test data and calculating UC using Christiansen's equation. The two methods compared within 3 percent. A more detailed explanation of Strong's method was given by Keller et al. (1967).

Strong continued on with this method to present a performance table for selecting the proper spacing of various sprinklers under different wind conditions. The double nozzle sprinklers was assumed to produce a profile between Christiansen's B and C profile, and the single nozzle sprinklers would produce the D profile. The general practice for representing wind effects was to reduce the effective diameter of cover 1 percent for each mile per hour of wind speed prior to using Christiansen's UC curves (Keller, et al., 1967).

Keller, Moynahan, and Ptacek (1971) presented a graphical method for estimating UC from basic UC curves. The curves were developed from data taken in essentially zero wind speed conditions. A shift ratio was developed to relate the amount various wind speeds shift the UC curves. A wind speed may be represented by reducing the diameter by the shift ratio before entering the basic zero wind UC curves. The UC curves are entered with a value of spacing along the main divided by the reduced diameter.

Keller, Moynahan, and Ptacek (1971) indicated tests with actual data found the above method to be reliable. The estimated UC values compared within ± 5 percent of the calculated UC values.

Classifying Sprinkler Tests Taken in Steady Wind

Moynahan (1972) found it necessary to classify sprinkler tests taken in steady wind before making an analysis of wind effects on sprinkler water distribution. It was important for each test to be assigned some index which gave information about the wind speed, wind direction, and wind variation that transpired during the test period. With this index, the capability of a test to represent a certain wind speed was determined. The location of the center of mass (C_m) of a sprinkler test pattern has been suggested by Moynahan (1972) to be a good index. Intuitively, C_m seems to be a valid index to represent the wind history of a single sprinkler test.

The elementary case of C_m shift is the drift of a vertically falling water drop caused by a horizontal wind velocity. A falling water drop is acted on by gravity and air resistance forces. Umback and Lembke (1965) conducted a wind tunnel study to establish a relationship between the wind drift of falling drops and wind velocity, drop diameter, and vertical distance through which the drops fell while in the wind tunnel. Their work resulted in the following equation:

$$\text{Drift} = (0.0198H^{1.83}\ V^{1.21})\ /\ D^{0.69} \qquad (7)$$

where H is the fall distance in the tunnel (feet), V is the wind velocity (feet per second), and D is the drop diameter (millimeters). The H and D in the equation may be treated as constants for a sprinkler situation in essentially steady wind; assigning H is equal to the maximum height of water jet trajectory and D is equal to the average drop diameter. Thus the drift is approximately equal to a constant multiplied by $V^{1.21}$.

In general, air resistance can be considered proportional to the first power of the velocity (Synge and Griffith, 1959). Bilanski and Kidder (1956) used this premise to compute the distance a drop of water would travel when trajected from a sprinkler nozzle. Their theoretical estimates concurred fairly well with actual test results indicating the use of air resistance proportional to the first power of velocity when the water jet has an initial velocity gives reliable results. Therefore, it seems justifiable to suggest the shift in C_m for a sprinkler test pattern is a reasonable measure of the average speed of the influencing wind during the test period.

Moynahan (1972) used the direction of C_m shift to give an indication of the average wind direction when the variation in direction was small. He limited his work to tests made in winds with very little direction variation. The object of considering the C_m shift of a sprinkler test pattern was to categorize the test as to the type of wind it was capable of representing.

Keller, Moynahan, and Ptacek (1971) introduced a dimensionless parameter, C_r, to compare the relative effect wind speed had on the stability of various sprinkler pattern profiles. The dimensionless parameter, C_r, was the ratio of shift in center of mass, C_m, of the sprinkler test pattern and the average effective radius, R_e, of the sprinkler under 0 to 3 mile per hour winds. The value of R_e was taken as the sprinkler radius averaged over the eight radial legs. The equation is,

$$C_r = 100 \left(\frac{C_m}{R_e} \right) . \tag{8}$$

Figure 2 was made as a plot of the C_r values versus effective average wind speed, W_e, for several tests.

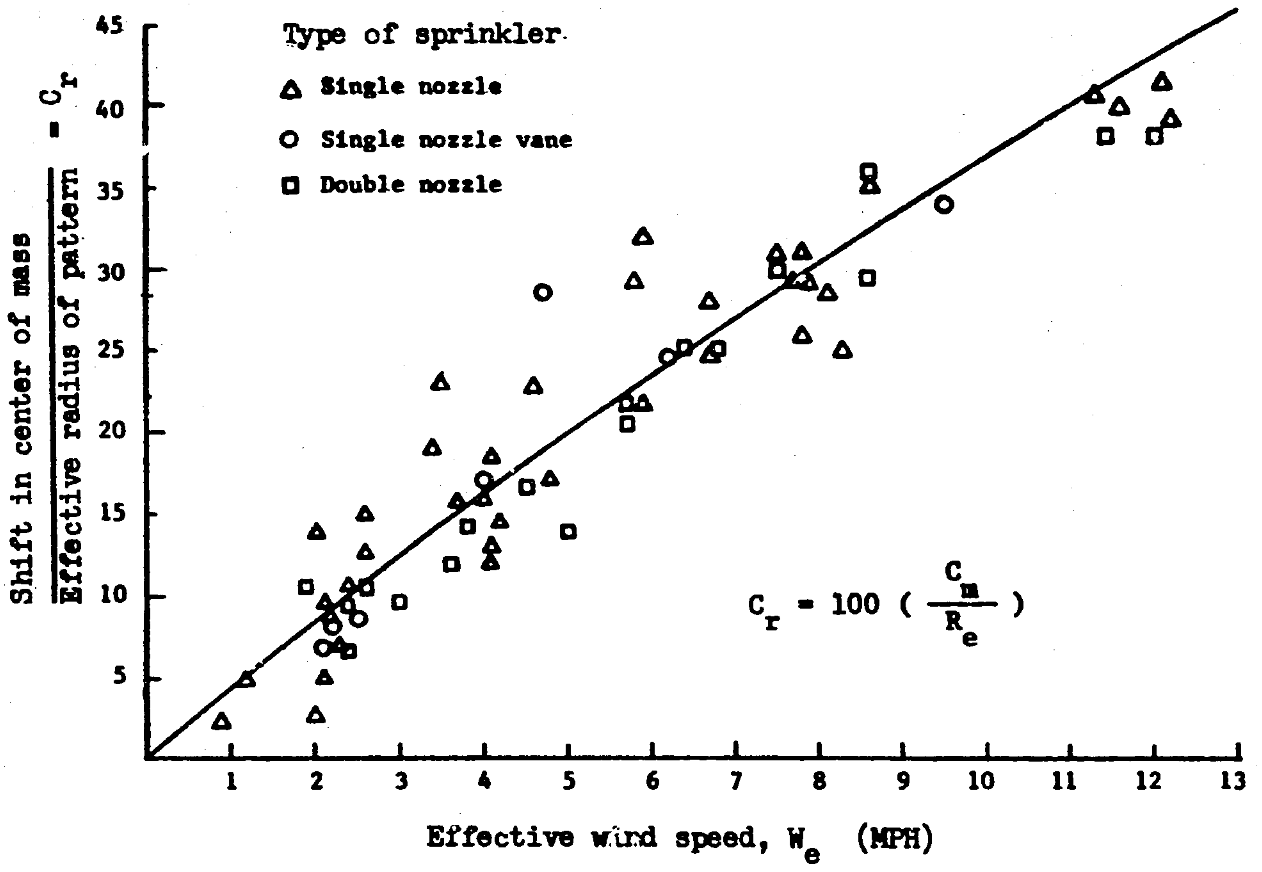


Figure 2. Shift in center of mass ratio, C_r, versus average effective wind speed, W_e, (Keller, Moynahan, and Ptacek, 1971).

ANALYTICAL METHOD AND PROCEDURE

Modeling Theory

The following assumptions used in this analysis are based upon the results of other workers as presented in the Review of Literature.

(1) The process of stacking sprinkler patterns to represent various winds is a valid process.

(2) The location of the center of mass (C_m) of a single sprinkler test pattern taken in steady wind reflects the wind conditions encountered during the test.

(3) For a test in steady wind, the shift in C_m can give a measure of average wind speed. The amount of shift is nearly proportional to the first power of wind speed.

(4) The C_m shift direction gives an indication of the average wind direction.

The purpose of this investigation is to propose and demonstrate a practical procedure to synthesize the influence of a wind history on a single sprinkler test pattern. The analytical technique relied on the following hypotheses:

(1) The shift of C_m in a wind of constant speed and variable direction compared with the C_m shift for steady wind gives an indication of the amount of wind direction variation. The maximum amount of C_m shift will occur when the wind direction is constant. Anything less than the maximum shift for an average speed indicates some variation in wind direction occurred during the sprinkler test period.

The degree of unsteadiness in wind direction can be depicted by a ratio W_a/W_e where W_a is the average wind speed measured during a test. W_e is the effective wind speed as estimated by the magnitude of shift in center of mass (C_m). W_e can be found using the curve developed by Keller, Moynahan, and Ptacek (1971) as shown in Figure 2. The numerical value of the W_a/W_e ratio will be equal to one for a pure wind blowing from a constant direction. When a variation of direction has occurred, the ratio will be some value greater than one. A check of the magnitude of wind direction variation using the W_a/W_e ratio indicates the pattern is adequate for representing a steady wind. Only test results exhibiting a steady wind influence ($W_a/W_e \approx 1$) are selected for use in stacking to represent a conglomerate total wind history.

(2) The C_m shift magnitude gives a measure of average wind speed in a pattern experiencing unsteady wind.

(3) A limited set of independent sprinkler test data can be manipulated and stacked to synthesize the effects of a wind history. This manipulation involves both rotation of test data to reflect any desired wind direction and the stacking of data from tests conducted at several wind speeds. Each pattern can be assigned any desired proportion of the wind history.

(4) Expected sprinkler performance can be synthesized from a limited amount of suitable test data, i.e., the wind history can be sufficiently characterized with a limited number of direction and speed readings.

Test Procedure

Center of mass parameter

The validity of using C_m as a parameter to define wind direction in unsteady wind will first be analyzed. A stacked pattern will be made to represent an unsteady wind's influence on a test pattern. The angle of C_m shift for the stacked pattern will be compared with the resultant angle obtained by vector addition of the individual contributing pattern shifts. This will indicate the reliability of using the C_m shift angle to define the average wind direction in an unsteady wind.

The hypothesis of using the C_m shift magnitude as an index of average wind speed will be checked. A stacked pattern will again be made to represent unsteady wind effects on a test pattern. The magnitude of the C_m shift of the stacked pattern will be compared with the expected C_m shift obtained by vector addition of the contributing pattern shifts. This will aid in determining the reliability of using the magnitude of C_m shift as a measure of average wind speed in an unsteady wind.

The value of utilizing the W_a/W_e ratio will subsequently be analyzed. The W_a/W_e ratio will be evaluated for a stacked pattern representing unsteady wind effects and compared with an analytical value obtained by vector addition.

Characterizing wind history

Various methods can be used to synthesize a wind history. The most appropriate method should be selected based on the type of sprinkler system of interest. When a single sprinkler pattern is overlapped upon itself at a specified spacing, the performance of a solid set system is synthesized. This synthesized performance pattern is only representative of the wind history experienced during the single sprinkler performance test.

Modeling a portable system to predict field performance requires the use of several single sprinkler test patterns each representing a wind history expected to occur in the field. Care must be taken to overlap the patterns in the order which the wind histories take place in the field. Branscheid and Hart (1968) found that when the proper sequence of overlapping was employed, the actual and predicted performance values agreed within allowable tolerances.

The method used in this work is the stacking process to create a single sprinkler pattern representative of a wind history. The effect of the wind history of interest is synthesized by stacking various patterns on top of each other. Each of the contributing patterns are assigned a relative weight proportional to the amount of influence they are to exert on the conglomerate pattern. The relative influence given by a contributing pattern is determined by the percent of time the particular wind (this contributing test pattern represents) is present in the wind history being modeled.

An unsteady wind can be fully described by a continuous record of wind speed and wind direction. For practical field analysis of wind effects on sprinkler distribution the wind history can be broken into a series of wind speeds from different directions. To use the concept of a series of average speed and direction components a selection must be made of the allowable range over which the wind speed and direction may be averaged. Accepting the premise that the C_m shift is a measure of the steady wind during a sprinkler test provides a tool to evaluate the allowable wind angle range over which an average direction can be used to represent all the wind occurring within the angle segment.

More specifically, it can be seen how applying an average wind direction effects the C_m shift. This would help in evaluating the error introduced by averaging.

As discussed previously it is desirable to simplify the wind history data as much as is practical prior to the modeling process. For modeling purposes it was decided any wind direction could be assigned to one of eight principle directions ordinarily utilized. The eight angles or segments normally utilized are the compass directions N, NE, E, SE, S, SW, W, and NW. The clockwise measured angles for these directions will be 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315° respectively. Any wind angle occurring within $\pm 22.5^\circ$ of these principle directions will be thought of as acting in the principle direction. In effect the circle of possible wind directions is divided in eight segments each comprised of 45°. The wind occurring within a segment is considered to act at the center of the segment. Such a segmented circle is illustrated by Figure 3.

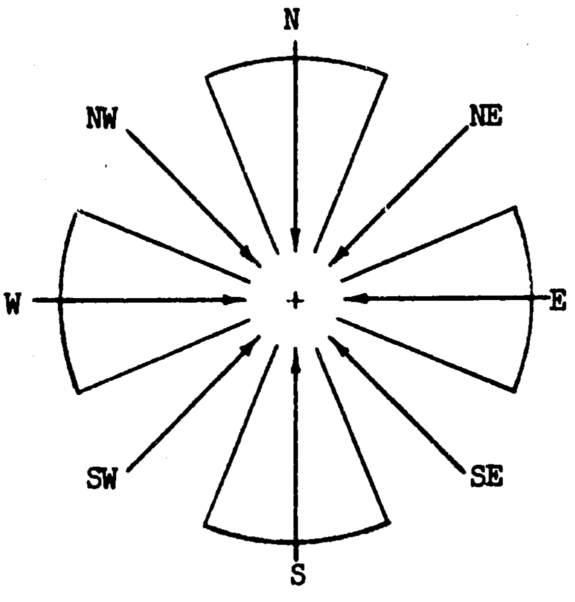
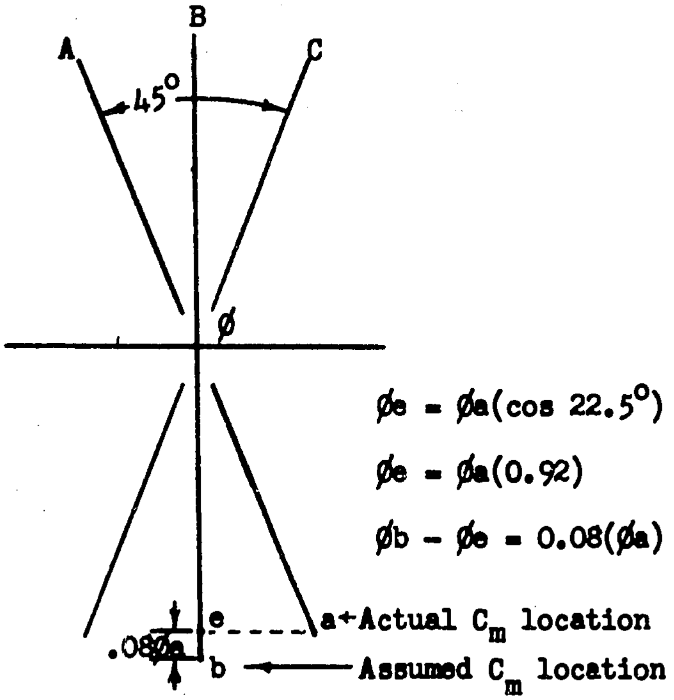


Figure 3. Compass circle divided into 45° angle segments indicating the grouping of wind directions.

The convention for assigning wind direction is the same as used by the United States Weather Bureau, i.e., the wind direction is taken as the direction the wind is coming from for an observer standing at the center of the compass circle.

A certain amount of error may be caused by assuming the wind as acting in one of eight possible directions for a specific interval of time. The amount of error introduced can be estimated by using the C_m shift, an index to wind effects on a sprinkler test pattern. Consider a 45° angle segment as shown in Figure 4.



$$\phi e = \phi a(\cos 22.5^\circ)$$

$$\phi e = \phi a(0.92)$$

$$\phi b - \phi e = 0.08(\phi a)$$

Figure 4. A 45° angle wind segment showing maximum error caused by using the median angle to represent wind direction.

The suggested method is to find the average wind speed in the segment $A\phi C$ and represent it as acting in direction $B\phi$. The maximum error in this procedure would occur when all the wind was concentrated at a segment boundary such as $A\phi$. For any other condition the average wind should lie nearer 0B and the error diminished. When all the wind of a specific time increment occurred at A0 the C_m would be located at point a. Assuming the wind came from B0 would position the C_m at point b where distance 0a = 0b. To be analytically exact the component of 0a in the 0b direction should be 0a($\cos 22.5^\circ$) or C_m should be located at point e. The error between points e and b is 0a($1 - \cos 22.5^\circ$) or 0.080a (an 8 percent error).

The more logical situation is when wind occurs within the segment. The error in using the median angle would be less if the wind was acting at 7.5°, 15°, and 22.5° from 0b for equal time intervals. The error then would be 0a[$(1 - \cos 7.5^\circ) + (1 - \cos 15^\circ) + (1 - \cos 22.5^\circ)$]/3 or 0a[0.039] which is less than 4 percent error and probably not significant for practical conditions. The validity of using eight 45° segments to categorize the wind direction was tested and the result is given later.

The sensitivity of a sprinkler pattern to wind direction change will be evaluated. Uniformity coefficient values of a stacked pattern will be compared with the UC values of a median angle pattern to determine the range where the median angle pattern no longer depicts the stacked pattern. The amount of wind direction variation in the stacked pattern will be increased in increments until the median angle pattern UC values no longer compare satisfactorily with the stacked pattern UC values.

The sprinkler pattern sensitivity to wind speed change will be evaluated in a simular analysis. The wind speed interval over which an average satisfactorily depicts the distribution uniformity will be determined. This will aid in understanding the allowable amount of averaging in the wind speed possible before a significant error is introduced.

Sprinkler testing procedure

A major portion of the sprinkler test data utilized in this work was supplied courtesy of Rain Bird Manufacturing Company, Glendora, California. The rest of the data was collected at the Utah State University Farm, Vernal, Utah. These tests were made to evaluate shift in the center of mass as an index to define unsteady wind and check the effect the stacking process has on the shift of C_m.

The test installation was made to comply with ASAE Recommendation: ASAE R330 "Procedure for Sprinkler Testing for Research Purposes", (see Appendix A for complete recommendations) except for the following deviations: (1) the collectors were 8 inches above the ground instead of 12 inches; (2) the rims of the collectors were from 1 to 2 inches above the crop of vegetative growth instead of 6 inches; (3) the wind measuring equipment was at a height of 9 feet instead of 13 feet.

One single nozzle sprinkler head was utilized for all the tests. The sprinkler had a 3/4 inch inlet and a 9/64 inch range nozzle. A new model 30 series sprinkler produced by Rain Bird Manufacturing Company with teflon—neoprene bearings was selected for the tests.

During the test the sprinkler head was tested for uniformity of rotation. The rates at 57 pounds per square inch (psi) varied between 0.75 revolutions per minute (rpm) and 0.80 rpm, and the discharge varied less than 1 percent.

Pressure gauges with dial indicators reading from 0 to 100 psi were used during the test. A gauge was inserted into the sprinkler riser to measure base pressure. Another gauge equipped with a pitot tube was used to measure pressure at the nozzle outlet.

The sprinkler head was mounted on a 3/4 inch diameter steel riser 27 inches in length. This riser height placed the sprinkler head 2 feet above the rims of the four collectors nearest the sprinkler.

The collectors were clear plastic quart size freezer containers 8 inches deep with a square open surface area 4 inches by 4 inches. The problem of having water splash out of the collectors was avoided by using these deep containers. Fifty milliliter graduated cylinders were utilized to measure the precipitation intercepted by the collectors (catch cans). The collectors were placed on the ground five feet apart in a grid measuring 95 feet on each side. The sprinkler was located at the center of the grid square 47.5 feet from the edges of the grid area. This test installation was utilized for all the single sprinkler pattern tests. It was decided using this unchanged test site for tests with several different winds would allow the summation of test data to represent a test of long duration with a composite wind history.

The discharge of the tested sprinkler head was measured before the test started. A plastic hose was placed over the nozzle and the time required to fill the 3.5 gallon bucket was determined. This measurement was repeated twice and the average value recorded. The nozzle pressure was measured with the pitot tube equipped gauge just prior to the beginning of the test.

As the sprinkler test began, the rotating-cup totalizing anemometer reading was taken and recorded in conjunction with wind direction and wet and dry bulb temperatures. These readings were taken at 15 minute intervals during the test. The average rotation rate of the sprinkler head was recorded for a 10 minute interval during each of the tests. The test duration was 60 minutes.

At the end of the test period the discharge rate and the nozzle pressure were again measured. The precipitation in the collectors was measured using a graduated cylinder capable of measuring to the nearest 0.5 milliliter.

Computer Program

A computer program was prepared to facilitate in making the evaluations and calculations performed in this investigation. The developed program is capable of rotating sprinkler pattern can catch data, stacking the data (summing point on point) of any number of sprinkler test patterns, overlapping sprinkler patterns for any number of desired spacing combinations, and computing the uniformity (UC) values for each of the respective spacings. See Appendix B for a listing of the computer program along with the necessary operating instructions.

Prior to utilizing a sprinkler test in the main program, all tests must undergo a preliminary analysis to locate the center of mass (C_m) of the test pattern. The center of mass of a single sprinkler test pattern is defined as the point where the moment of the can catch values (weighted by the distance from the sprinkler head) sum to zero. The C_m location can be visualized as the balancing point of the mass of water emitted from the sprinkler during a test period. The calculation for C_m is made using a small program which is also listed in Appendix B. Each test is categorized by the shift in C_m for the specific wind speed the data is capable of representing.

The process of modeling wind influence on a sprinkler test pattern is achieved with the aid of the computer in the following sequence:

(1) A selection of wind speed to be modeled is made based on the wind history of interest.

(2) A set of sprinkler can catch data is selected (from patterns categorized by the amount of C_m shift) to represent the wind speed influence.

(3) The effect of each increment of wind direction, as prescribed by the wind history, is achieved by rotation of the sprinkler test data such that the C_m shift direction is exactly opposite the required wind direction. The pattern rotation is accomplished by rotating the test pattern grid such that the "during test" wind direction corresponds to the required wind direction. The points on the rotated grid are calculated by linear interpolation which, using the four surrounding points, eliminates the idea of a defined surface for the can catch test data. A comparison has been made between linear interpolation and interpolation utilizing a defined curved surface equation as presented by Seginer (1969). Results indicate the two methods give nearly identical answers.

(4) The rotated sprinkler pattern is assigned a relative weight equivalent to the percent of time this particular wind speed and direction occurs in the wind history being modeled.

(5) Utilizing the wind history as a basis, another set of sprinkler data is selected and the above four steps are repeated to obtain a representation of the next wind speed. The resulting pattern data is then stacked point for point upon the previously obtained pattern.

(6) The above five steps are repeated until each part of the modeled wind history is represented by a corresponding element in the total stacked pattern.

(7) Given this conglomerate sprinkler test pattern representing a complete wind history and the spacing combinations of interest, the computer overlaps the pattern upon itself offset by the proper spacing and calculates the uniformity coefficient values (using Christiansen's equation) for each of the respective spacing combinations.

RESULTS AND DISCUSSION

Center of Mass Shift Parameter in Unsteady Wind

To test quantitatively the effect of variable wind on sprinkler water distribution, a significant amount of test data must be available. A major restriction in this work was the lack of pure steady wind tests. It is essential the tests utilized in the analysis have as little inherent wind variation as possible. Tests are compatable and can be properly stacked in a modeling process only when all test conditions (except wind) are equal. A list of sprinklers for which test data was used and the wind conditions during the respective tests can be found in Table 1. The wind speed given is the average wind speed measured during the test using a totalizing anemometer. The wind direction is taken as opposite the direction of center of mass shift.

Determination of wind direction in unsteady wind

One objective of this work is to test the validity of using center of mass (C_m) shift as a parameter to define average wind direction of a variable wind. It is accepted the C_m shift direction is adequate for depicting wind direction of essentially constant wind patterns. It is important to determine how the C_m of a test pattern shifts with direction variation of an unsteady wind. Several patterns from the sprinkler with the same nozzle size and pressure were superimposed upon each other to obtain a conglomerate single sprinkler test pattern depicting unsteady wind effects. The direction of shift in C_m was then calculated for this stacked pattern. The direction of C_m shift was

Table 1. List of sprinkler tests conducted in several steady winds.

Test No.[a]	Nozzle size	Pressure (PSI)	C_m shift (FT)	Wind Speed (MPH)	Wind Relative direction[b]
2608	9/64	40	4.8	2.6	-1.8
1677	9/64	40	10.2	7.8	36.5
2427	9/64	40	15.2	12.2	24.2
111*	9/64	57	6.2	3.4	27.7
112*	9/64	57	8.1	3.6	37.7
113*	9/64	57	4.8	3.1	80.3
114*	9/64	57	3.2	2.4	-90.8
115*	9/64	57	5.4	3.3	-40.7
1297	5/32	40	2.0	1.2	110.7
1294	5/32	40	1.5	2.0	-127.7
1290	5/32	40	3.3	2.3	93.1
1303	5/32	40	2.2	2.5	40.2
1542	5/32	40	3.1	2.8	19.8
1298	5/32	40	4.0	3.5	36.9
1543	5/32	40	6.5	3.7	-139.2
1287	5/32	40	6.9	4.5	33.8
1295	5/32	40	4.7	4.9	12.2
1292	5/32	40	7.5	5.1	40.2
1649	5/32	40	8.0	5.5	-91.0
1300	5/32	40	8.7	6.9	34.4
1296	5/32	40	9.4	7.6	22.4
1302	5/32	40	9.7	8.1	40.6

Table 1. Continued

Test No.[a]	Nozzle size	Pressure (PSI)	C_m shift (FT)	Wind	
				Speed (MPH)	Relative direction[b]
16133	11/64	50	2.3	1.7	146.3
2420	11/64	50	7.1	3.7	26.9
2418	11/64	50	9.8	5.9	27.9
2422	11/64	50	12.6	6.7	37.6
1663	3/16	50	7.5	4.0	78.8
1667	3/16	50	13.8	7.7	52.8
2559	3/16	50	18.7	11.6	55.3
1657	3/16	60	2.4	1.2	-6.8
2586	3/16	60	15.0	7.8	60.7
2483	3/16	60	13.7	8.1	84.1
2585	3/16	60	19.5	11.3	77.0
29	7/32	35	4.1	2.2	-39.4
9	7/32	35	8.5	4.0	-103.3
33	7/32	36	17.0	9.5	152.8
2569	11/64 x 3/32	50	6.4	3.8	39.7
2567	11/64 x 3/32	50	9.7	5.7	48.8
2570	11/64 x 3/32	50	11.3	6.4	16.6
2582	11/64 x 3/32	50	17.1	11.4	77.5
2574	11/64 x 3/32	50	17.2	12.0	69.7

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[a] Rain Bird Manufacturing Co. test data and number designation except where indicated.

[b] Wind direction is referenced from north. Plus (+) angle clockwise, minus (-) angle measured counterclockwise.

* Test conducted at Utah State University Farm, Vernal, Utah.

compared with the expected C_m shift direction which was the vector sum of the C_m's for each of the contributing elements. The results, as shown in Figure 5, indicate a good correlation between the stacked pattern C_m shift direction and the resultant vector direction. A perfect correlation is represented by the diagonal line which passes through the origin and through 60° and 60°. The results indicate the C_m shift direction of a sprinkler pattern is a useful parameter depicting the resultant angle of contributing wind direction vectors. When the patterns are stacked upon each other each test exerts a proportional influence on the conglomerate pattern.

Determination of average wind speed in unsteady wind

Another objective of this analysis was to check the validity of using the magnitude of C_m shift as a parameter to define the average wind speed experienced during a single sprinkler test in unsteady wind. Keller, Moynahan, and Ptacek (1971) indicated if wind direction was constant there was essentially a straight line relationship between average wind speed and the magnitude of C_m shift in a steady wind. (See Figure 2.) It was decided to stack data from several tests using progressive summation to synthesize an unsteady wind situation. Tests similar in every respect except wind direction were summed or stacked together. The process began with one test where wind direction equaled 0°; another test with wind direction greater than 0° was then stacked on top of it. The next tests were added in order of increasing wind direction angle. As the patterns were stacked the extent of wind direction variation increased. After each pattern was added the C_m shift for the total pattern was found. This shift was compared with

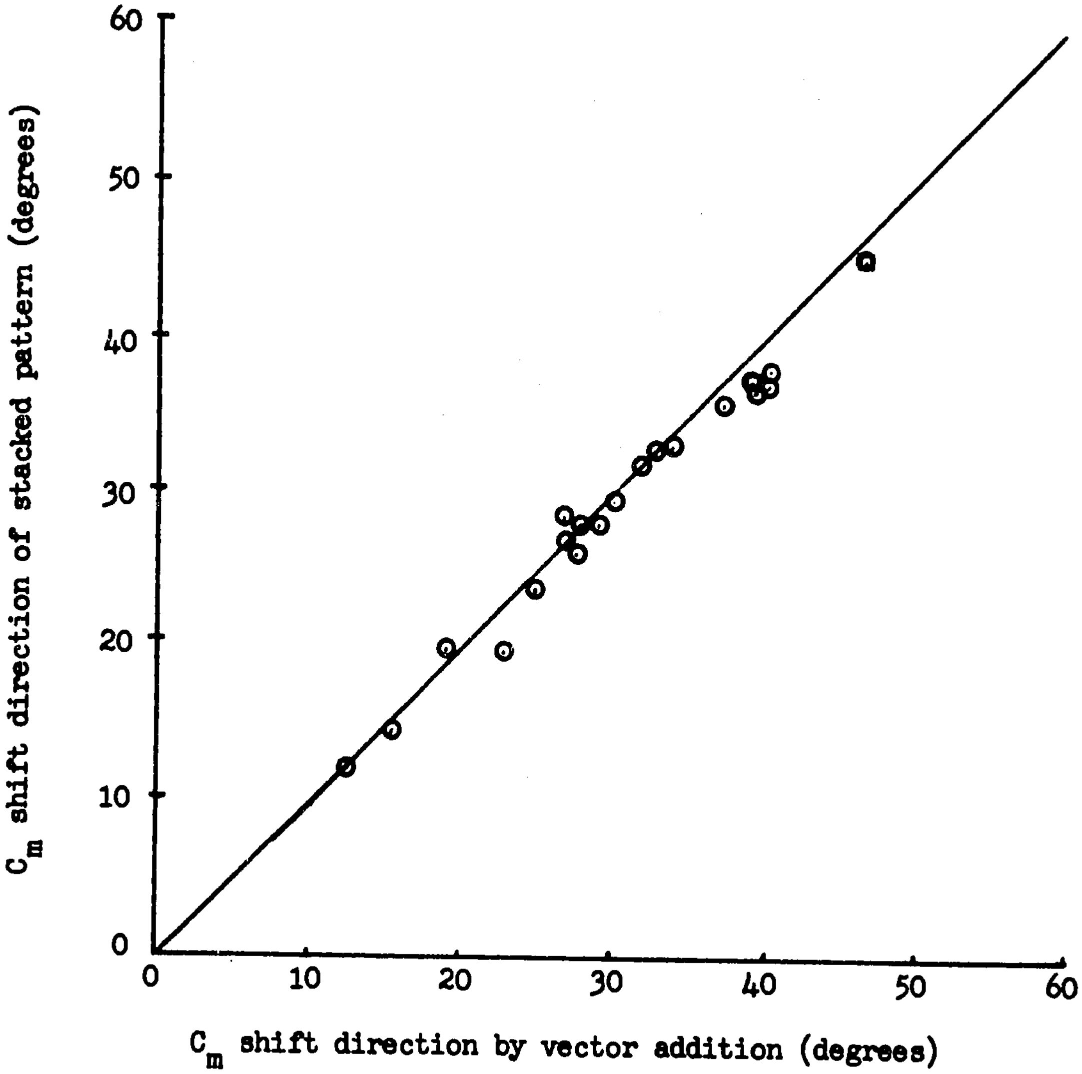

Figure 5. Plot of the C_m shift direction for a stacked pattern versus the resultant vector direction of the contributing pattern shifts.

the vector sum of the individual C_m shift of the contributing patterns. Results of the progressive summation analysis are given in Table 2. The wind direction difference is the magnitude of the wind angle over which the contributing patterns varied. The difference between the C_m shift magnitude does not significantly increase with increased wind direction difference. The close correlation of the C_m stacked pattern and C_m vector sum is encouraging. If each of the contributing patterns are thought of as representing a portion of a wind history then the stacked pattern represents a total wind history and the location of the center of mass depicts the average wind speed of the wind history. This value is equivalent to the resultant of the vector sum of the contributing winds.

Determination of wind variation

In the preceding section it was suggested the C_m shift gives an indication of wind direction variation during a test period. It was shown in Table 2 the magnitude of C_m shift depicts the average effective wind speed, W_e, occurring during the test period. The average wind speed, W_a, for the test is given by the anemometer readings. The difference between W_e and W_a should give a measure of direction variation.

The effects of wind direction variation were achieved by rotating a test pattern in 10° intervals (0°, 10°, 20°, etc.) and stacking these rotated patterns to get one total test pattern. The location of C_m was then found for the total pattern. One pattern was used; therefore, the average wind speed of the single pattern must be the same as the average wind speed of the stacked pattern, W_a. The

Table 2. Center of mass shift of a stacked pattern compared with the vector sum of the individual contributing test pattern shifts.

Wind direction range (degrees)	Center of mass shift (feet)		
	Stacked pattern	Vector resultant	Difference
10	6.2	6.2	0.0
10	3.8	3.9	0.1
10	5.0	5.7	0.7
20	5.6	6.1	0.5
20	6.1	6.6	0.5
20	5.6	6.2	0.6
30	5.9	6.3	0.4
30	6.2	6.7	0.5
30	5.7	6.2	0.5
50	5.9	6.0	0.1
80	5.1	5.8	0.7
100	4.6	5.3	0.7
170	3.5	3.5	0.0
210	3.5	4.3	0.8
220	3.0	3.9	0.9
260	2.4	3.3	0.9

effective wind, W_e, calculated by using C_m shift and Figure 2 would be equal to W_a if no direction variation occurred. The ratio W_a/W_e gives an indication of the amount of direction variation occurring in the stacked sprinkler test pattern. Table 3 gives results and values of the W_a/W_e ratio. Any ratio value greater than one indicates the center of mass shift is less than expected at the average wind speed. The results show the ratio increased in value as the wind direction variation increases. The second ratio was arrived at analytically by vector summation. The two ratios closely agree indicating the W_e value is the resultant of the contributing winds. If W_e is less than the average wind speed the wind direction varied during the sprinkler test and the pattern in question does not represent the effects of a pure steady wind. This wind ratio test can be applied to any sprinkler test pattern where the sprinkler rotates uniformly so C_m is at the sprinkler head in no wind conditions.

Sprinkler Pattern Sensitivity to Wind Direction Change

Several simplifying assumptions, if made properly, can significantly reduce the amount of work involved in modeling unsteady wind effects on sprinkler performance. The object of this phase of the study is to gain an understanding of how sensitive a sprinkler distribution pattern is to wind direction variation. It has been suggested a median angle be used for depicting the wind direction of all wind occurring within a 45° angle segment. The validity of this suggested method can be checked by comparing uniformity (UC) values of an average wind angle pattern with those of a stacked variable direction pattern. The stacked pattern was created by repetitive summation of a test

Table 3. The effects of wind direction variation on the W_a/W_e ratio, W_a is the average test period wind speed, and W_e is the effective test pattern wind speed.

Wind direction of contributing tests*	C_m (FT)	W_a (MPH)	W_e (MPH)	Ratio W_a/W_e	Group average W_a/W_e	Analytical value W_a/W_e
0,10,20	3.77	2.3	2.3	1.00	1.02	1.01
	8.43	4.2	4.2	1.00		
	11.51	6.8	6.6	1.02		
	13.34	7.7	7.4	1.04		
	19.20	11.3	11.0	1.03		
0,10,20,30,40	3.69	2.3	2.2	1.05	1.05	1.03
	8.28	4.2	4.1	1.03		
	11.20	6.8	6.5	1.05		
	12.98	7.7	7.2	1.07		
	18.83	11.3	10.7	1.06		
0,10,20,30, 40,50,60	3.58	2.3	2.2	1.05	1.08	1.07
	8.06	4.2	4.0	1.05		
	10.80	6.8	6.2	1.10		
	12.63	7.7	7.0	1.10		
	18.27	11.3	10.4	1.09		
0,10,20,30,40, 50,60,70,80	3.44	2.3	2.1	1.10	1.13	1.11
	7.73	4.2	3.8	1.11		
	10.33	6.8	5.9	1.15		
	12.19	7.7	6.7	1.15		
	17.54	11.3	9.9	1.14		

*Wind direction given in degrees measured clockwise from north.

pattern rotated in 10° increments up to 90°, e.g. 10°, 20°, 30°, etc. The average angle pattern is simply test data rotated so the wind comes from the average direction. Table 4 gives the resulting UC values for both the stacked pattern and the median angle pattern in a 3.7 mph wind speed. The difference in the UC values increases as the included angle increases. As expected the technique of using the median direction to represent the entire segment produces a greater error as the segment size increases. Data for several other wind speeds can be found in Appendix C.

A comparison of the uniformity values was made to estimate the error caused by using an average direction to represent all the wind occurring within the 45° segments. The difference between the uniformity coefficient of the stacked pattern, UC_{sp}, and the uniformity coefficient of the median angle pattern, UC_{map}, was found. Results are listed in Table 5 and plotted against the wind speed values as shown in Figure 6. The UC values are for a 30 x 40 and 30 x 50 foot sprinkler spacing. This plot is valid only for these particular spacings but it does give an indication of the error introduced by using a median direction. The amount of error increases rapidly at wind speeds greater than 7.0 mph. However, since UC is accurate only to ± 3 percent (Fry et al., 1969), a median wind direction can be used without introducing significant error. At wind speeds greater than 8.0 mph the error may be as great as ± 5 percent for using the one direction to represent all the wind within the 45° angle segment. The tendency is for the single pattern uniformity values to be less than the actual values. This conservative error is not as critical as an over predicting error. The use of 45° angle segments to describe wind

Table 4. Values of uniformity coefficient for stacked patterns and median angle patterns under a 3.7 mph wind speed.

Angle of contributing elements[a]	Uniformity coefficient values						Ave. difference[b]
	Stacked pattern			Median angle pattern			
	30x40	30x50	40x50	30x40	30x50	40x50	
0 and 10	92.4	85.5	82.3	92.3	85.5	82.0	0.1
0 to 20	92.4	85.0	82.7	92.2	84.8	82.1	0.3
0 to 30	92.3	84.3	82.7	92.2	84.6	82.6	0.2
0 to 40	92.5	84.0	82.9	92.0	83.6	82.7	0.4
0 to 50	92.8	83.7	83.1	91.2	82.1	81.3	1.7
0 to 60	93.2	83.5	83.3	91.4	81.6	81.3	1.9
0 to 70	93.3	83.2	83.4	91.6	81.7	81.6	1.7
0 to 80	93.5	83.0	83.5	91.7	81.4	80.8	2.0
0 to 90	93.7	83.1	83.6	92.5	81.0	81.2	1.9

[a] The range of pattern rotation is given, i.e., 0 to 30 is a stacked pattern containing 0, 10, 20, and 30 degree rotated patterns.

[b] The absolute difference between the stacked pattern and the median angle pattern uniformity coefficients is given.

Table 5. Uniformity coefficient values at 30 x 40 and 30 x 50 foot spacings for stacked patterns (UC_{sp}) and the median angle patterns (UC_{map}) in a 45° angle segment at several wind speeds.

Wind Speed	Uniformity Coefficient Values					
	30 x 40 foot spacing			30 x 50 foot spacing		
	UC_{sp}	UC_{map}	Difference	UC_{sp}	UC_{map}	Difference
2.0	90.9	91.0	0.1	88.6	88.2	0.4
2.1	95.8	95.1	0.7	91.1	91.3	0.2
3.7	92.7	91.6	0.9	83.9	82.9	1.0
3.8	94.7	94.1	0.6	91.6	90.7	0.9
4.0	93.7	92.8	0.9	88.6	87.8	0.8
5.7	92.0	91.5	0.5	90.5	90.0	0.5
5.9	91.6	90.6	1.0	88.1	87.4	0.7
6.4	89.8	88.6	1.2	87.9	86.9	1.0
7.7	85.6	83.6	2.0	87.4	85.0	2.4
7.8	86.4	83.1	3.3	85.9	83.5	2.4
8.1	89.7	87.9	1.8	91.3	88.7	2.6
9.4	92.7	90.2	2.5	83.1	81.7	1.4
11.3	87.2	81.7	5.5	83.9	78.3	5.6
12.0	86.3	81.9	4.4	75.4	72.6	2.8

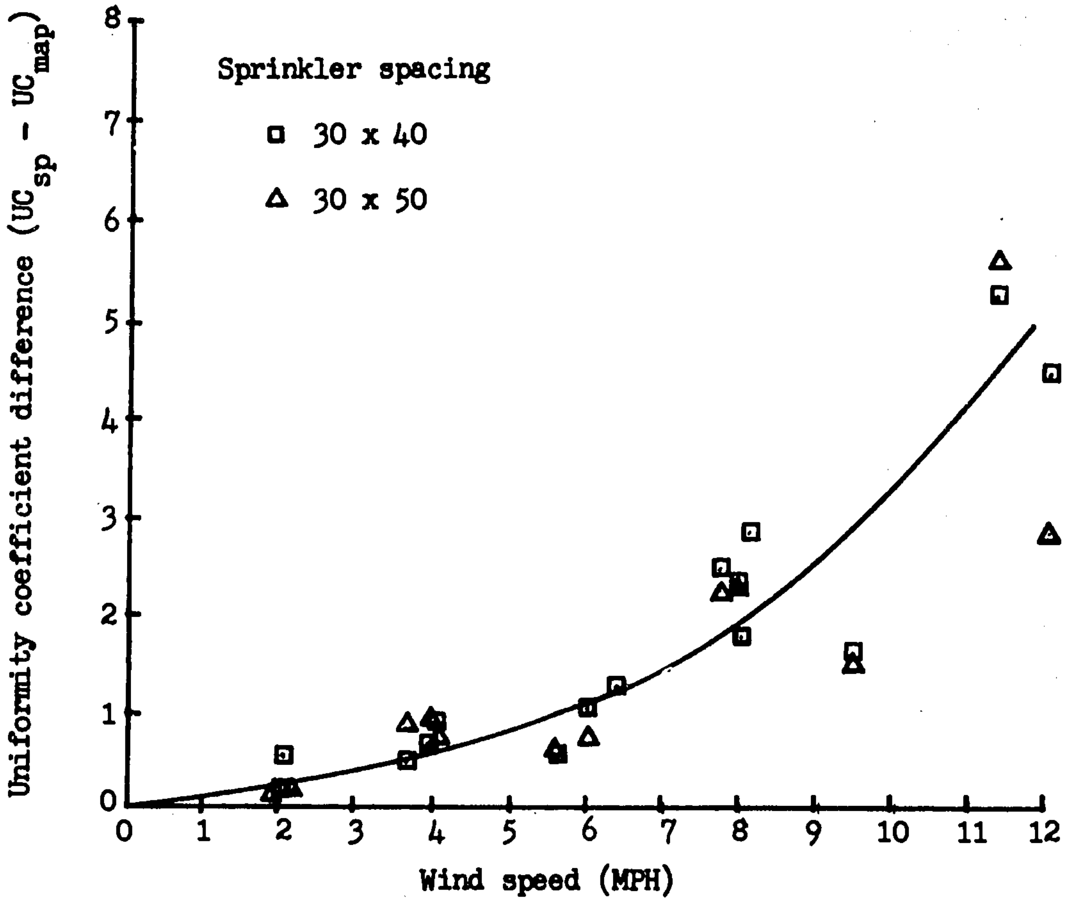

Figure 6. Difference between stacked pattern UC value and median angle pattern UC value for 45° angle segment for 30x40 and 30x50 foot spacings.

direction is adequate for practical field conditions. However, it must be remembered that significant error can be introduced when dealing with high wind speeds.

Sprinkler Pattern Sensitivity to Wind Speed Change

The relationship between uniformity coefficient and wind speed is not linear. However, the possibility of finding an interval where the relationship is close to linear should not be overlooked. It is felt there is a wind speed interval in which assuming a straight line relationship between wind speed and distribution uniformity produces reliable results. This phase of the work is essentially an effort to find that wind speed interval which should result in a better understanding of a sprinkler pattern sensitivity to wind speed changes.

In the interval where wind speed and UC have a linear relationship, it would be possible to predict the test pattern and ultimately the UC values of an intermediate wind speed if the maximum and minimum wind sprinkler test patterns were available. To restate the concept, given the interval of linear relationship and the upper and lower boundary wind patterns, any interior wind speed pattern could be modeled by linear interpolation. This approach was taken for various wind speed intervals. The uniformity values of the synthesized wind speed test pattern (UC_{syn}) were compared with the UC values of an actual test made at the wind speed being modeled (UC_{pure}). These average UC values, as listed in Table 6, were obtained using six different spacings, i.e., 30 x 40, 30 x 50, 40 x 40, 40 x 50, 40 x 60, and 60 x 60 foot spacing combinations. The average of the absolute difference between the two values was plotted against the interval between

Table 6. Uniformity coefficient values of a synthesized wind speed test, UC_{syn}, compared with the UC values of an actual test made at the specified wind speed, UC_{pure}, averaged over six spacings.

Wind speed Interval (MPH)	Average Uniformity Coefficient Values Synthesized Pattern	 Pure Pattern	Difference
0.3	87.2	84.6	2.6
1.0	86.6	85.5	1.1
1.2	87.0	85.2	1.8
1.4	88.4	86.9	1.5
2.2	89.9	87.1	2.8
2.5	88.5	87.8	0.7
2.6	82.1	80.3	1.8
3.3	87.7	87.4	0.3
3.3	90.6	87.4	3.2
3.9	89.0	88.3	0.7
4.3	88.2	87.5	0.7
4.3	88.1	86.7	1.4
4.3	89.3	86.9	2.4
5.7	81.6	76.5	5.1
6.3	68.5	64.8	3.7
7.3	89.7	86.9	2.8
7.6	87.8	81.9	5.9
7.6	80.8	74.5	6.3
7.6	83.2	76.5	6.7
8.2	88.6	81.6	7.0

the upper and lower wind speeds utilized in the modeling process. Results of the comparison are given in Figure 7. A large amount of scatter can be observed in the data points; however, it is noted that when the interval is less than 5 mph, the error does not exceed ± 3 UC percentage points. From Figure 7 it can be suggested that the error is ± 3 percent or less when a 5 mph wind speed interval is utilized. This indicates a sprinkler pattern can be modeled for a specific wind speed given test data collected in wind speeds greater and smaller than the model speed and differing by 5 mph or less. Implications are that a pattern for any low wind speed can be synthesized given data for 0, 5, and 10 mph wind speeds. It must be remembered the lack of sufficient data resulted in the analysis being restricted to tests with wind speeds not greater than 12 mph.

Predicting Field Performance in Variable Wind

Suggested method for modeling wind influence

The basic goal of this work is to suggest a method for modeling the wind influence on sprinkler water distribution and to ultimately predict sprinkler field performance in variable wind. In summarizing the previous analysis, a relatively simple modeling process can be suggested. Implicit in this process is for the following to be available:

(1) Sprinkler test patterns for the nozzle of interest conducted in steady winds differing by 5 mph (or less) increments, e.g., 0, 5, 10 mph wind speeds.

(2) Knowledge of the probable wind conditions anticipated during the time of sprinkling, i.e., a reliable wind history.

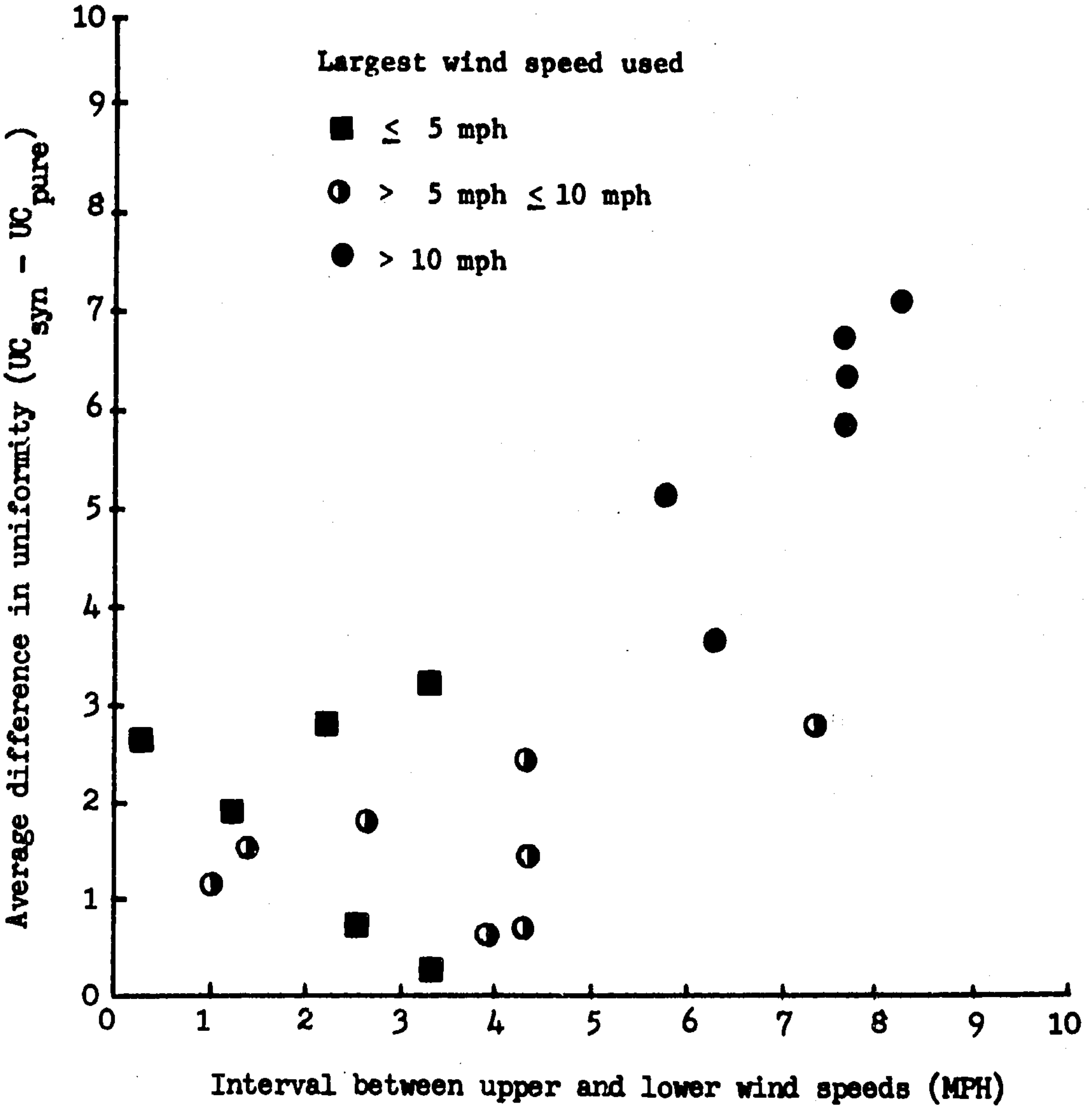

Figure 7. Average difference in uniformity coefficient values versus interval between upper and lower wind speeds used in the modeling process.

(3) Computer program as contained in Appendix B and use of a digital computer.

With this information it becomes a simple process to arrive at an expected sprinkler water distribution pattern and consequently a prediction of sprinkler performance:

(1) Divide wind data into eight 45° angle segments.

(2) Assign each segment the appropriate relative weight based on percent of time wind occurs within the segment.

(3) Within each segment, group wind speed into 5 mph intervals and find the average wind speed for each interval.

(4) Assign each wind speed the appropriate relative weight based on percent of time wind occurs in each 5 mph interval.

(5) Synthesize the wind speed patterns, rotate to the center of the appropriate segments, and stack together using the computer program.

The resulting pattern reflects the unsteady wind described by the modeled wind history. The computer overlaps the pattern for any desired spacing combination and calculates the resulting uniformity coefficients.

Performance prediction in actual wind

Actual wind data collected at Salt Lake City, Utah, was utilized as an example of applying the procedure for predicting distribution uniformity. The list of percentages in Table 7 is a summary of hourly wind observations during July from 1951 through 1960. The wind directions can be grouped as indicated by the dashed lines and the percentage frequencies combined within the groups. For this case, the wind speed groups are not equal but the groups are small so the median value of

Table 7. Summary of percentage frequencies of wind direction and speed for month of July at Salt Lake City, Utah from 1951 through 1960.

Segment number	Compass direct.	Hourly observations of wind speed (in miles per hour)					Total	Ave. speed
		0-3	4-7	8-12	13-18	19-24		
1	N	.7	2.7	3.4	.5		7.3	7.8
	NNE	.2	1.4	1.6	.2		3.5	7.9
2	NE	.5	1.3	.9	.1		2.8	6.5
	ENE	.2	.5	.3	.1		1.0	6.4
3	E	.2	.9	.4	.2	+	1.9	8.3
	ESE	.4	1.6	2.1	.7		4.9	8.6
4	SE	.6	4.7	9.2	2.4	+	17.1	9.3
	SSE	.7	4.4	11.6	4.4	+	22.5	10.4
5	S	.7	3.2	6.1	3.3	+	14.6	10.8
	SSW	.2	.7	.8	.4	+	2.3	9.8
6	SW	.3	.7	.6	.3	+	1.9	8.5
	WSW	.1	.6	.2	.2		1.2	8.2
7	W	.1	.7	.5	.3		1.7	8.4
	WNW	.2	.6	1.1	.4		2.4	9.0
8	NW	.3	2.1	3.0	1.1		6.5	9.1
	NNW	.2	2.0	2.8	.7		5.7	8.8
	Calm	2.8					2.8	
	Total	8.5	28.4	44.7	15.0		100.0	9.1

Plus (+) indicates more than 0 but less than 0.5.
Source: Reichelderfer, F.W. Climatography of the United States No. 82 - 42, U.S. Dept. of Commerce, Weather Bureau, p 9, 1963.

each will be used to represent the interval. This median value is then modeled utilizing the pure steady wind patterns. These median values are 1.5, 5.5, 10.0, and 15.0 mph wind speeds.

The sprinkler head and pressure of interest is the 11/64 x 3/32 inch nozzle at 50 psi. In Table 1 we see there are test data for this sprinkler available for five wind speeds, i.e., 3.8, 5.7, 6.4, 11.4, and 12.0 mph. The wind data in Table 7 requires 1.5, 5.5, 10.0, and 15.0 mph wind test patterns to sufficiently synthesize the wind history. In this example the lowest wind speed test (3.8 mph) will be used to represent the low wind speed group and the 12.0 mph will be utilized to represent the highest wind speed group. The required wind speed will be synthesized by interpolation using the following proportions:

0- 3 mph ≃ 3.8(1.0)
4- 7 mph ≃ 5.7(1.0)
8-12 mph ≃ 6.4(0.28) + 11.4(0.72)
13-18 mph ≃ 12.0(1.0)

The resulting patterns are then assigned a percentage value taken from Table 7 and subsequently rotated to have the wind direction act through the center of the respective segments. This step is repeated until each percentage in Table 7 is represented by an element in the stacked pattern. It is important to remember the percentage frequencies are essentially the percent of the time the various wind conditions occur. The stacking of the percentage weighted patterns results in a single pattern representing the total wind history with all of the time represented by a specific wind situation.

Table 8. Tests used to model example wind history and the relative weight and direction of each.

```
SPRINKLER TEST PATTERN SYNTHESIZED BY A COMBINATION OF THE FOLLOWING PATTERNS
   NOZZLE SIZEDOUBLE       PRESSURE     50
    TEST NO. 2569      WIND SPEED=  3.8MPH.      WIND ANGLE   11.25      RELATIVE WEIGHT  .009

    TEST NO. 2569      WIND SPEED=  3.8MPH.      WIND ANGLE   56.25      RELATIVE WEIGHT  .007

    TEST NO. 2569      WIND SPEED=  3.8MPH.      WIND ANGLE  101.25      RELATIVE WEIGHT  .006

    TEST NO. 2569      WIND SPEED=  3.8MPH.      WIND ANGLE  146.25      RELATIVE WEIGHT  .013

    TEST NO. 2569      WIND SPEED=  3.8MPH.      WIND ANGLE-168.75       RELATIVE WEIGHT  .009

    TEST NO. 2569      WIND SPEED=  3.8MPH.      WIND ANGLE-123.75       RELATIVE WEIGHT  .004

    TEST NO. 2569      WIND SPEED=  3.8MPH.      WIND ANGLE  -78.75      RELATIVE WEIGHT  .003

    TEST NO. 2569      WIND SPEED=  3.9MPH.      WIND ANGLE  -33.75      RELATIVE WEIGHT  .005

    TEST NO. 2567      WIND SPEED=  5.7MPH.      WIND ANGLE   11.25      RELATIVE WEIGHT  .041

    TEST NO. 2567      WIND SPEED=  5.7MPH.      WIND ANGLE   56.25      RELATIVE WEIGHT  .018

    TEST NO. 2567      WIND SPEED=  5.7MPH.      WIND ANGLE  101.25      RELATIVE WEIGHT  .025

    TEST NO. 2567      WIND SPEED=  5.7MPH.      WIND ANGLE  146.25      RELATIVE WEIGHT  .091

    TEST NO. 2567      WIND SPEED=  5.7MPH.      WIND ANGLE-168.75       RELATIVE WEIGHT  .039

    TEST NO. 2567      WIND SPEED=  5.7MPH.      WIND ANGLE-123.75       RELATIVE WEIGHT  .013

    TEST NO. 2567      WIND SPEED=  5.7MPH.      WIND ANGLE  -78.75      RELATIVE WEIGHT  .013

    TEST NO. 2567      WIND SPEED=  5.7MPH.      WIND ANGLE  -33.75      RELATIVE WEIGHT  .041

    TEST NO. 2570      WIND SPEED=  6.4MPH.      WIND ANGLE      .00     RELATIVE WEIGHT  .280
THIS WIND SPEED COMBINES TO SYNTHESIZE INTER. SPEED.
    TEST NO. 2582      WIND SPEED= 11.6MPH.      WIND ANGLE      .00     RELATIVE WEIGHT  .720

    TEST NO. 2582      WIND SPEED= 10.0MPH.      WIND ANGLE   11.25      RELATIVE WEIGHT  .050

    TEST NO. 2582      WIND SPEED= 10.0MPH.      WIND ANGLE   56.25      RELATIVE WEIGHT  .012

    TEST NO. 2582      WIND SPEED= 10.0MPH.      WIND ANGLE  101.25      RELATIVE WEIGHT  .025

    TEST NO. 2582      WIND SPEED= 10.0MPH.      WIND ANGLE  146.25      RELATIVE WEIGHT  .208

    TEST NO. 2582      WIND SPEED= 10.0MPH.      WIND ANGLE-168.75       RELATIVE WEIGHT  .069

    TEST NO. 2582      WIND SPEED= 10.0MPH.      WIND ANGLE-123.75       RELATIVE WEIGHT  .008

    TEST NO. 2582      WIND SPEED= 10.0MPH.      WIND ANGLE  -78.75      RELATIVE WEIGHT  .016

    TEST NO. 2582      WIND SPEED= 10.0MPH.      WIND ANGLE  -33.75      RELATIVE WEIGHT  .058

    TEST NO. 2574      WIND SPEED= 12.0MPH.      WIND ANGLE   11.25      RELATIVE WEIGHT  .007

    TEST NO. 2574      WIND SPEED= 12.0MPH.      WIND ANGLE   56.25      RELATIVE WEIGHT  .002

    TEST NO. 2574      WIND SPEED= 12.0MPH.      WIND ANGLE  101.25      RELATIVE WEIGHT  .009

    TEST NO. 2574      WIND SPEED= 12.0MPH.      WIND ANGLE  146.25      RELATIVE WEIGHT  .068

    TEST NO. 2574      WIND SPEED= 12.0MPH.      WIND ANGLE-169.75       RELATIVE WEIGHT  .037

    TEST NO. 2574      WIND SPEED= 12.0MPH.      WIND ANGLE-123.75       RELATIVE WEIGHT  .005

    TEST NO. 2574      WIND SPEED= 12.0MPH.      WIND ANGLE  -78.75      RELATIVE WEIGHT  .007

    TEST NO. 2574      WIND SPEED= 12.0MPH.      WIND ANGLE  -33.75      RELATIVE WEIGHT  .018
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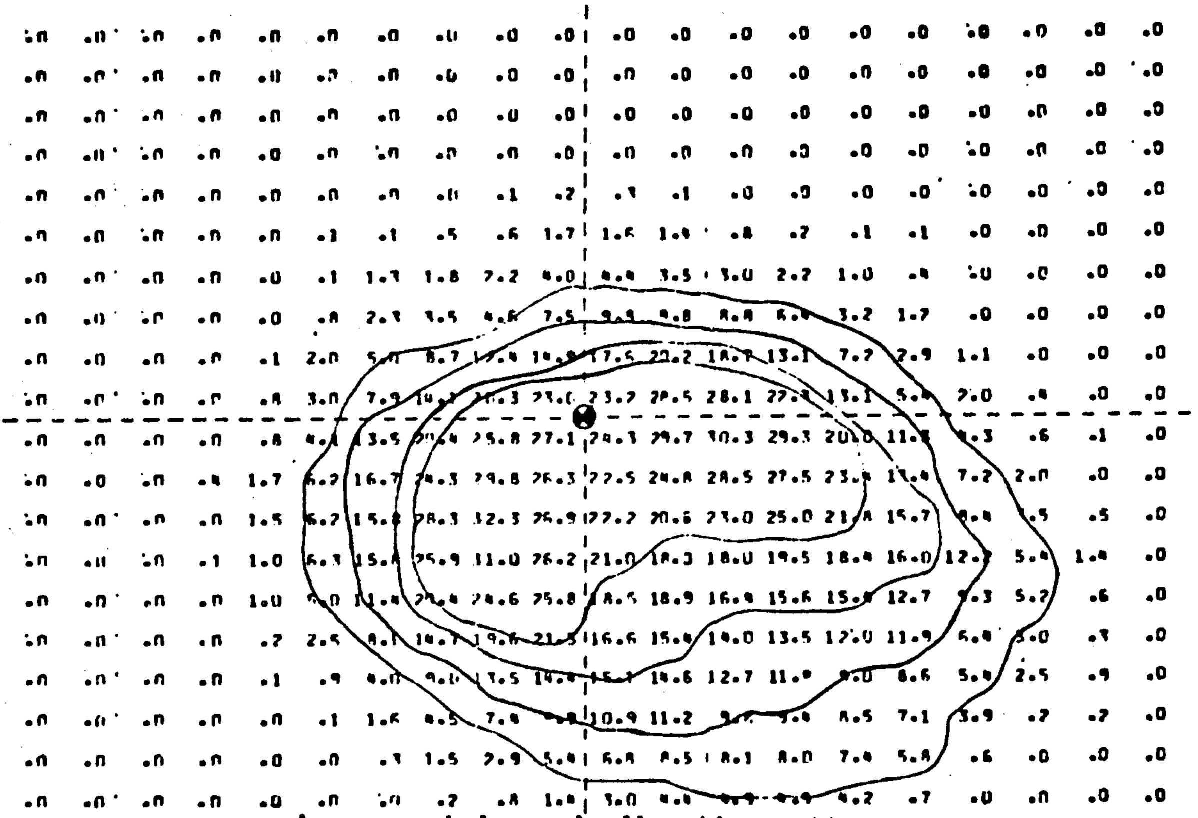
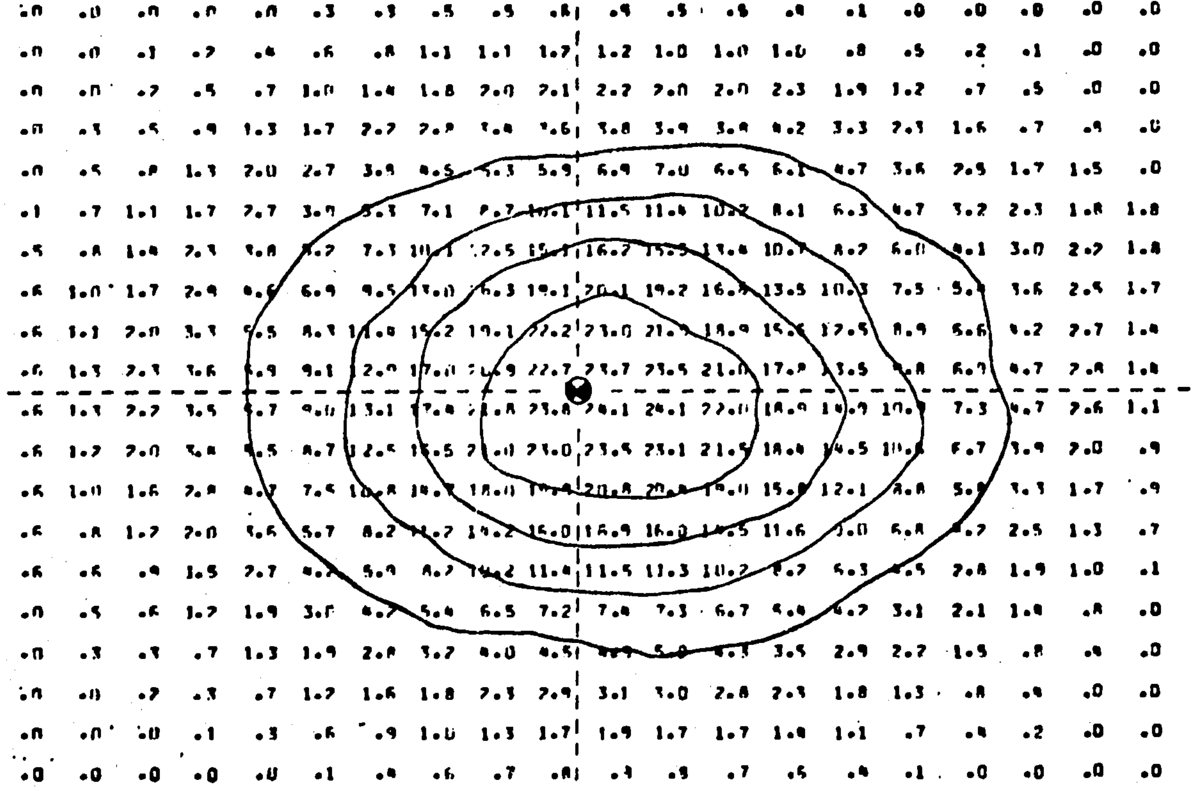


Average wind speed—direction pattern.



Complete wind history pattern.

⊗ SPRINKLER LOCATION

Figure 8. Resulting test patterns using two methods to model wind data.

Table 9. UC values for average wind speed—direction pattern and a complete modeled wind history pattern at six spacings using a 11/64 x 3/32 inch nozzle at 50 psi.

Spacing (Feet)	UC Values Average speed—direction pattern	 Modeled wind history pattern	UC difference
30 x 40	89.1	97.7	8.6
30 x 50	84.5	92.7	8.2
40 x 40	85.4	96.8	11.4
40 x 50	80.0	92.3	12.3
40 x 60	67.7	81.2	13.5
60 x 60	59.9	76.1	16.2

Both patterns have the same average wind speed and prevailing wind direction. Table 9 shows the modeling process creates a pattern with uniformity values at least 8 UC percentage points higher than the average speed-direction pattern for these spacings. The higher UC values can be explained by the changes in speed and direction which creates a smoothing effect improving distribution evenness. This effect is totally ignored in using the average wind speed and the prevailing wind direction to depict wind influence on sprinkler water distribution.

The higher UC values for the overall wind history are similar in magnitude to the results of Pair (1968). He compared individual irrigation UC values and found they were lower than the accumulated seasonal UC values. This suggests the individual irrigations had slight variations in wind direction but the accumulated or stacked irrigations exhibit the effect of a total seasonal wind history.

CONCLUSIONS

A method was suggested to model unsteady wind effects on a sprinkler test pattern utilized in predicting water distribution uniformity. The wind effects are modeled based on time percentage of occurrence for wind speed and direction. Wind speeds ranging from 0 to 12 miles per hour were investigated.

The method requires a simplifying assumption, i.e., wind speed is averaged within 5 mph intervals and assigned to act at the center of a 45° angle segment to represent that segment. It was found this assumption did not significantly reduce the accuracy of uniformity predictions.

The concept of using the location of the center of mass to define unsteady wind was investigated. (Center of mass is located at the balancing point of the mass of water emitted from a sprinkler during a test. In zero wind C_m is located at the sprinkler.) Work involving the C_m shift concept resulted in the following conclusions:

(1) C_m shift depicts wind direction experienced during a sprinkler test.

(2) C_m shift in a test pattern is essentially the weighted resultant of wind speed during the test.

(3) Any desired C_m shift can be achieved by stacking compatible patterns with proportional weights based on their respective C_m shifts.

(4) C_m shift does not directly describe uniformity coefficient values for a test pattern.

(5) The ratio W_a/W_e gives a measure of wind direction variation within a test. It is essential to remember the value of the C_m parameter comes in categorizing a single sprinkler test pattern prior to using it for modeling.

The usefulness of the suggested procedure comes as a result of the relatively small amount of data required. The influence of any low wind speed can be synthesized by a limited amount of patterns conducted for a particular sprinkler nozzle-pressure combination. The primary requirements for wind test pattern data are they have little or no wind variation occurring during the test and they cover the necessary range of wind speeds with a 5 mph or smaller interval between successive speeds. This predicting technique is particularly good for areas which receive repetitive cyclic winds as the wind in these areas can be sufficiently characterized and a reliable wind pattern found with a limited amount of testing.

A major restriction of this study was the lack of pure steady wind test patterns. The method proposed should be helpful in organizing sprinkler test programs to include only the test conditions required to give data for a few reliable pure steady wind patterns. It also provides a basis for eliminating the less important tests which add little to the knowledge of sprinkler performance in wind.

Sprinkler tests utilized in this analysis were limited to wind speeds of 12 mph or less. It is recommended single sprinkler test data be collected for higher wind speeds while concurrently operating an adjacent system in a test of long duration. The correlation between the suggested procedure and the actual field results could then be evaluated.

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APPENDIXES

Appendix A

ASAE Recommendations

ASAE Recommendation: ASAE R330

PROCEDURE FOR SPRINKLER DISTRIBUTION TESTING FOR RESEARCH PURPOSES

Developed by the Sprinkler Irrigation Committee; approved by ASAE Soil and Water Division Standards Committee, adopted by ASAE December 1969.

SECTION 1—PURPOSE AND SCOPE

1.1 This Recommendation has the following two purposes:

1.1.1 To provide a basis for the accumulation of data on the distribution characteristics of sprinklers.

1.1.2 To provide a uniform method for the presentation of the data described in paragraph 1.1.1.

1.2 The data collected are to be of such extent and accuracy as to assist sprinkler system designers in making rational decisions regarding the water distribution pattern of sprinklers.

1.3 This Recommendation describes the types and methods of obtaining and recording pertinent climatic data. There must be a sufficient amount of data so that apparent conflicts between results of different investigators can be resolved.

1.4 No attempt is made here to define analysis procedures.

SECTION 2—SPRINKLER DESCRIPTION AND SELECTION

2.1 Number of sprinklers. Single sprinkler tests only are covered in these procedural recommendations. It is generally desirable to perform more than one test under ostensibly the same sprinkler operating and climatic conditions. Each test shall be reported separately and not combined with others in any way.

2.2 Selection of sprinklers. Any sprinkler used in these tests shall be chosen at random from normal production runs.

2.3 Description of sprinkler. The sprinkler shall be described in such a way that a completely unambiguous reference can be made to it at a future date. This description shall include, but not necessarily be limited to, the following:

Make
Model name and number
Serial number or other identifying mark
Nozzle diameter(s) and description(s)
Entrance fitting description (size, type, etc.)
Type of bearing
Other identifying information (e.g., straightening vanes, type of drive, etc.)

SECTION 3—TESTING INSTALLATION

3.1 Sprinkler location and installation.

3.1.1 The sprinkler shall be located in an area which has either a bare surface or less than 3 in. (8 mm) of vegetative growth. The land shall have a maximum slope of 1 percent for sprinklers discharging less than 35 gpm (2.21 liters per sec) and 2 percent for other sprinklers. The site shall be located such that there is a minimum clear distance upwind of the pattern area of 6 heights for each mile per hour (0.45 meter per sec) of wind speed up to a maximum of 30 heights for winds of 5 mph (2.23 meters per sec) or greater, and a minimum clear distance downwind of the pattern area equal to 5 heights of any downwind windbreak. A map showing location and height of windbreaks shall be included on the Standard Data Presentation Form. Tests shall not be run when these conditions are not satisfied.

3.1.2 The center of the main nozzle of the sprinkler shall be 2 ft (0.6m) above the average elevation of the tops of the 4 nearest collectors on land slopes of 1 percent or less, or 2 ft (0.6m) higher than the top of the highest collector on land slopes greater than 1 percent.

3.1.3 The sprinkler riser shall be vertical within 1 deg.

3.2 Collector description and location.

3.2.1 All collectors used to measure distribution shall be the same. They shall be designed such that the water does not splash out and such that evaporation is kept to a minimum. The collector shall be completely described on the data sheet. If an evaporation suppressant is used, its type and method of application shall be reported.

3.2.2 A square grid pattern of collectors shall be used, with the spacing between collectors being any whole number. The sprinkler shall be located in the center of a grid square (midway between 4 adjacent collectors). A minimum of 80 collectors shall receive water during a test. The position of the collectors shall be maintained such that the entrance portion is horizontal, as estimated by visual means.

3.2.3 The average above-ground height of the tops of the 4 collectors nearest the sprinkler shall be either 3 ft (0.9 m) above the ground, or, as an alternative, 1 ft (0.3 m) above the ground. This distance shall be reported as "collector height." For land slopes of 1 percent or less, the collectors shall be in a horizontal plane. For land slopes greater than 1 percent, the collectors shall be in a plane parallel to the average land slope.

3.3 Climatic measuring equipment and location.

3.3.1 The wind movement during the test period shall be measured with a rotating-cup totalizing anemometer, or a device of equal or better accuracy. Floating ball type devices are not satisfactory. The wind direction shall be measured with a wind vane on the basis of 8 points of the compass.

3.3.2 Wind measuring equipment shall be located within the clear area as described in paragraph 3.1 but outside the sprinkler pattern, and at a height of 13 ft (4m).

3.3.3 Dry and wet bulb temperature measurements shall be made at a location where the microclimate is essentially unaffected by the operation of the sprinkler. This will normally be upwind of the pattern area.

SECTION 4—MEASUREMENTS

4.1 Sprinkler pressure.

4.1.1 The nozzle pressure is defined as the pitot-static pressure at the vena-contracta of the jet from the main (largest) nozzle. It shall be measured with a pitot tube and a pressure-indicating device accurate to within ±2 percent (at the sprinkler pressure) and reported.

4.1.2 The base pressure is defined as the pressure head at the sprinkler. This shall be measured at a point on the riser at least 2 riser diameters from any change of direction of flow or change in pipe cross-sectional area. Position shall be recorded. The base pressure shall vary not more than ±3 percent during a test.

4.2 Sprinkler flow. The flow through the sprinkler shall be measured and reported to an accuracy of ±3 percent. Volumetric measurements under the test pressure, made with a stop-watch and a container, or with a calibrated water meter, are satisfactory.

4.3 Sprinkler rotation. The rate of rotation of the sprinkler shall be measured and reported. The uniformity of rotation through the 4 quadrants shall be measured and reported.

4.4 Climatic data.

4.4.1 Wind measurements shall be taken at 15 maximum intervals of minutes. Distance shall be recorded to the nearest 0.1 mile (0.16 kilometer) of movement and directions to the nearest octant. Direction shall be keyed to one of the principal axes of the Standard Data Presentation Form.

4.4.2 Wet and dry bulb temperatures shall be measured at maximum intervals of 15 minutes.

4.5 Depth of application. The depth of application in each collector shall be determined to an accuracy of ±2 percent of the average application depth and reported in a table showing the location of the collector relative to the sprinkler (see Standard Data Presentation Form).

SECTION 5—TEST DURATION

5.1 Test duration. The preferable test duration is 1 hour. Other test durations may be used, but the circumstances and time must be clearly stated on the test sheet. Sprinklers shall be started and stopped at the same position and true total time recorded.

SECTION 6—REPORTING

6.1 Information to be recorded. The data outlined in Sections 2, 3, 4 and 5 shall be recorded on forms similar to those shown in Figs. 1 and 2. A separate set of sheets shall be prepared for each sprinkler test.

6.2 Deviations from recommended procedure. Deviations from the recommended procedure shall be indicated on the Standard Data Presentation Form for Sprinkler Distribution Tests.

6.3 Additional data. Additional data on the conduct of a test should be included if it will benefit the system designer or help explain vagaries in results.

Test Conditions

Testing Agency____________________ Date ____________________ Test No.__________

Sprinkler Specifications (Par. 2.3)______________________________________

____

Test Location __________________________ Weather __________________________

1. Vertical distance from riser gage to nozzle, in. (Par. 4.1.2) ____________________
2. Inside diameter of riser, in. ____________________________________
3. Collector height, ft. (Par. 3.2.3) ________________________________
4. Collector entrance diameter, in. (Par. 3.2.1) __________________________
5. Sprinkler height, ft. (Par. 3.1.2) ________________________________
6. Flow rate, gpm (Par. 4.2) ____________________________________
7. Description of collector (Par. 3.2.1) ______________________________

____

____

____

8. Evaporation suppressant used __________________________ Volume/collector __________________
9. Data during test:

Time	Wind		Temp, °F		RH, %	Rotation rate, sec per full rev					Pres. psi	
	Mile	Dir.	DB	WB		Full	1st Q	2nd Q	3rd Q	4th Q	Noz	Base

10. Map of test area. Give the following:
    a. Location of sprinkler.
    b. Location of climatic measurement equipment.
    c. Wind direction during test period.
    d. Distance from sprinkler to *all* windbreaks (upwind, downwind, and to side).
    e. Heights of all windbreaks

This test ______ does ______ does not meet the criteria for sprinkler testing set forth in ASAE R330, Procedure for Sprinkler Distribution Testing for Research Purposes.

FIG. 1—STANDARD DATA PRESENTATION FORM, Test Conditions

Testing Agency ______________________ **Date** ______________________ **Test. No.** __________

Sprinkler Specifications ____

____

Test Location ______________________ **Weather** ______________________

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____ ____

Above depths in inches x 100. Mark locations of sprinkler with plus (+) sign. Indicate prevailing wind direction by an arrow and give its least angle of deviation from a line parallel to one of the principal axes of this sheet. Gird spacing is________ft.

FIG. 2—STANDARD DATA PRESENTATION FORM, Map

Appendix B

Computer Programs

Shift in Center of Mass Calculation

Input Procedure

Data Cards

First Card:

Column	
1- 5	Test Number
6-10	Number of rows and columns of cans in the sprinkler test. The cans must be symmetrical about the sprinkler and the cans per row must equal the cans per column.
11-15	Catch-can spacing.

Second Card:

The actual can-catch values are read in, beginning with this card, using a F4.1 format, 20 values per card. Each can must be allowed a location on the data card. The field may be left blank for zero values.

Any number of sprinkler tests can be read in by repeating the data card setup as outlined above, i.e. the first card of each test set must contain the test number, number of rows and columns, and the catch-can spacing.

Output

The program computes the magnitude (in feet) and the direction of the shift in the center of mass of the wind affected single sprinkler test pattern. The shift angle is referenced from North (plus angle clockwise).

The input catch-can values are printed out for each test.

CENTER OF MASS CALCULATION PROGRAM

```
      DIMENSION  CR(24.24)
    2 READ(5.101.END=3) IIT      .N.SPACE
C     IIT = TEST NO.
C     ANGLE = SHIFT ANGLE
C     N = NO OF COLLECTOR ROWS
  101 FORMAT(2I5.F5.0.2F5.1)
      I = 0
      J = 0
      IT = N/2*2-N
   12 READ (5.102) ((CR(I.J).J=1.N).I=1.N)
  102 FORMAT(20F4.1)
      WRITE(6.103) IIT
  103 FORMAT(5X.' TEST NO.'.I7)
C
C     SHIFT IN CENTER OF MASS
 2041 XS=0.
      XM=0.
      YS=0.
      YM=0.
      DO 1 I=1.N
      DO 1 J=1.N
 2043 CC = CR(I.J)
      XM=XM+SPACE*FLOAT(J  )*CC
      YM=YM+SPACE*FLOAT(I  )*CC
      XS=XS+CC
    1 YS=YS+CC
      XC=XM/XS
      YC=YM/YS
      IF (IT .LT. 0) XG=FLOAT(N/2+1)*SPACE
      IF (IT .EQ. 0) XG=(FLOAT((N/2)+0.5))*SPACE
      YG=XG
      XD=XG-XC
      YD=YG-YC
      ALPHA=ATAN2(YD.XD)
      ALPHA=ALPHA*57.296-90.
      D=SQRT(XD**2+YD**2)
      DO 2039 I=1.N
 2039 WRITE(6.105) (CR (I.J).J=1.N)
105   FORMAT(/.5X.24F5.1)
      WRITE(6.106) ALPHA . D
 106  FORMAT(3X.//'  SHIFT ANGLE= '.F7.1.8X.' CG SHIFT='.F7.1)
      GO TO 2
    3 STOP
      END


                NO  DIAGNOSTICS.
```

Computer Program to Model Wind Effects

Input Procedure

Data Cards

First Card:

Column	
1-5	Number of spacing combinations to be investigated.

Second Card:

Column	
1-4	Spacing on the lateral as a proportion of the effective diameter.
5-8	Spacing of the mainline as a proportion of the effective diameter.

There must be the same number of spacing combinations read in as indicated in the first data card. The spacing combinations are read in consecutively starting at the beginning of the second card using a 20 F 4.2 format, 10 spacing combinations per card. It may take more than one card depending on the number of spacing combinations desired.

Third Card:

Column	
1-5	Number of cans in the rows and columns of the sprinkler test. The cans must be symmetrical about the sprinkler. When the sprinkler is midway between four cans the number of cans is even. If the sprinkler is located on a grid point the number of cans in a row or column will be odd.
6-10	Catch-can spacing.

11-15	Number of different wind speed test patterns. This must be equal to the number of test patterns read in to be included in the stacking process.
16-20	Number of different wind directions each wind speed test pattern is rotated to prior to stacking. Each wind speed test pattern is rotated to the required angles before the computer continues on to the next speed.
21-25	Test pressure (in PSI) for the sprinkler test.
26-31	Test nozzle size.

Fourth Card:

Column	
1- 5	Test number.
6-13	Shift in center of mass.
14-21	Initial wind angle of the test pattern (opposite C_m shift direction) referenced from North (plus angle clockwise).
22-29	Effective diameter. The effective diameter can be set at 100 so the proportion used on the 2nd card can be multiplied by 100 to equal the sprinkler spacing.
30-37	Desired grid spacing after interpolation for intermediate grid points. This spacing must be divisionable evenly into the can spacing and must not be equal to the can spacing.
38-45	First required wind direction (angle to which test grid is rotated).
46-53	Relative weight the test pattern is given for this wind speed and direction.
54-61	Average wind speed of the test.

62-69	The variable used to combine two test patterns prior to rotation and stacking. A (2.0) is placed in this field for the first test of the combination and a (1.0) is placed in this field for the second test of the combination. For all other times this field is blank.

Fifth Card:

The actual can catch values are read in beginning with this card using a F4.1 format, 20 values per card. Each can must be allowed a location on the data card. The field may be left blank for zero values.

Remaining Cards: (When more than one wind direction is required for each wind speed test.)

One angle and one relative weight is read in per card until the number of required wind directions are satisfied.

Additional Sets of Test Data:

Additional sets of test data are read in by repeating the card setup order beginning with the fourth card. The number of sets of test data must be equal to the number of wind speeds punched on the Third Card (Column 11-15).

Output

The program takes each set of test data and rotates it to the required angle and reduces each can-catch value by the desired fraction (relative weight). The test number, wind speed, wind direction, and relative weight are printed out. The weighted tests are stacked together and the resulting total pattern is printed out. The center of mass is located for this pattern and the uniformity coefficient is computed for each spacing combination. The location of the center of mass is printed out. Next the uniformity values for each spacing is printed out showing the spacing (in feet) along the lateral and the main.

COMPUTER PROGRAM LISTING

```
C     PROGRAM TO ROTATE AND STACK SPRINKLER TEST GRIDS
C
      DIMENSION C(36,36), CR(36,36),WINWT(20),WTCC(36,36) ,A(100,60),
     $CE(100,100),ILS(60),IMS(60),SL(60),SM(60) ,B(60,60) ,CSN(36,36)
      WRITE(6,99)
 99   FORMAT(1H1)
      READ(5,100) NSR
C     NSR=NUMBER OF SPACING COMBINATIONS TO BE INVESTIGATED
100   FORMAT(5I5)
      READ (5,908) (SL(M),SM(M),M=1,NSR)
C     SL(M)=SPACING ON THE LATERAL AS PERCENT OF EFFECTIVE
C           DIAMETER
C     SM(M)=SPACING ON THE MAIN AS PERCENT OF EFFECTIVE
C           DIAMETER
  908 FORMAT(20F4.2)
  2   READ(5,101,END=3) N,SPACE,NWIN,NDIR,NPRES,NOZ
C     N=DIMENSION OF THE SPRINKLER PATTERN TO BE READ IN
C        (NOTE=MUST BE SYMETRICAL ABOUT THE SPRINKLER)
C     IF N IS EVEN THE SPRINKLER IS MIDWAY BETWEEN 4 ADJACENT
C        COLLECTORS
C     IF N IS ODD THE SPRINKLER IS LOCATED ON COLLECTOR POINT
C     SPACE=SPACING BETWEEN COLLECTOR POINTS
C     NWIN = NO. OF WIND SPEED PATTERNS
C     NDIR=NO. OF DIRECTIONS TO WHICH PATTERNS ARE ROTATED
C     NPRES=NOZZLE PRESSURE
C     NOZ = NOZZLE SIZE
101   FORMAT(I5,F5.1,3I5,A6)
      XCOR = 0.
      YCOR = 0.
      IT=N/2*2-N
      NN=N
      ISPACE=SPACE
      WRITE(6,2040) NOZ,NPRES
 2040 FORMAT(//,' SPRINKLER TEST PATTERN SYNTHESIZED BY A COMBINATION OF
     $ THE FOLLOWING PATTERNS'/5X,'NOZZLE SIZE',A6,5X,'PRESSURE',I6)
      DO 1220 I=1,36
      DO 1220 J=1,36
 1220 C(I,J) = 0.0
      DO 2044 IKE = 1, NWIN
      ICOUNT = 0
  777 READ(5,1001) ITEST,CG,ANGLE,DIA,S2,REQDIR,WINWT(IKE),WNSPED,SYN
C     ITEST=TEST NUMBER OF DATA (FOR IDENTIFICATION PURPOSES)
```

```
C      CG=SHIFT IN CENTER OF MASS
C      ANGLE=DIRECTION FROM WHICH WIND IS BLOWING,PLUS ANGLE IS
C            CLOCKWISE MEASURED FROM NORTH
C      DIA=EFFECTIVE DIAMETER OF SPRINKLER (ZERO WIND)
C      S2=DESIRED GRID SPACING AFTER INTERPOLATION FOR
C         INTERMEDIATE POINTS
C      REQDIR= DESIRED DIRECTION OF WIND
C      WINWT =  THE RELATIVE AMOUNT THIS WIND SPEED AND DIRECTION WILL
C         INFLUENCE THE SYNTHESIZED PATTERN
C      WNSPED = THE WIND SPEED REPRESENTED BY THE TEST
C      SYN=2 IF NEXT 2 PATTERNS ARE TO BE COMBINED
C         TO SYNTHESIZE AN INTERMEDIATE WIND SPEED
C         PRIOR TO BEING WEIGHTED AND STACKED
 1001 FORMAT(I5,8F8.3)
      DO 85 I=1,NSR
      ASPM=SM(I)*DIA/S2
      ASPL=SL(I)*DIA/S2
      ISPL=ASPL
      ISPM=ASPM
      ASPL2=ISPL
      ASPM2=ISPM
      RM=ASPM-ASPM2
      RL=ASPL-ASPL2
      IF(RM .GE. 0.5) ISPM=ISPM+1
      IF (RL .GE. 0.5) ISPL=ISPL+1
      ILS(I)=ISPL
   85 IMS(I)=ISPM
      READ(5,102) ((C(I,J),J=1,N),I=1,N)
C     C(I,J)=SINGLE SPRINKLER TEST PATTERN DATA
  102 FORMAT(20F4.1)
      GO TO 106
  103 READ(5,104) REQDIR,WINWT(IKE)
  104 FORMAT(2F8.2)
      ICOUNT = ICOUNT + 1
  106 CONTINUE
      DIR = REQDIR/57.29578
      XCOR=( COS(DIR)*WNSPED)*WINWT(IKE) +XCOR
      YCOR=( SIN(DIR)*WNSPED)*WINWT(IKE) +YCOR
      ANG1 = REQDIR
      ALPHA = ANG1 - ANGLE
      ND=N/2+1
      IF(IT.EQ.0) RAD=(FLOAT(N/2)-0.5)*SPACE
      IF(IT.LT.0) RAD=(N/2)*SPACE
      ALPHA=ALPHA/57.29578
      N1=N+1
      DO 4 I=1,N
      DO 4 J=1,N
      IF(IT.EQ.0) GO TO 12
      IF(I.EQ.ND .AND.J.EQ.ND)   GO TO 6
12    X=FLOAT(J-1)*SPACE-RAD
      Y=RAD-FLOAT(I-1)*SPACE
      XL=SQRT(X*X+Y*Y)
      IF(IT.EQ.0) GO TO 9
      IF (J .NE. ND) GO TO 9
      IF (I .GT. ND) BETA=-1.570795
      IF (I .LT. ND) BETA=1.570795
      GO TO 10
```

```
    9 BETA=ATAN2(Y,X)
   10 SA=SIN(BETA+ALPHA)
      CA=COS(BETA+ALPHA)
      X=XL*CA+RAD
      Y=RAD-XL*SA
      IF (ABS(X-RAD) .LE. .01   ) GO TO 11
      IF(X.GE.0.) GO TO 70
      IX=X
      XT=FLOAT(IX/ISPACE-1)*SPACE
      GO TO 71
70    IX=X
      XT=FLOAT(IX/ISPACE)*SPACE
71    IF(Y.GE.0.) GO TO 72
      IY=Y
      YT=FLOAT(IY/ISPACE-1)*SPACE
      GO TO 73
72    IY=Y
      YT=FLOAT(IY/ISPACE)*SPACE
73    XTP=XT+SPACE
      YTP=YT+SPACE
      II=0
      T=(RAD-Y)/(X-RAD)
      IF (ABS(T) .LE. .00001) GO TO 27
   39 YL=RAD-YT
      XL=YL/T
      YL=RAD-YL
      XL=RAD+XL
      J1=1
      IF((XT-XL) .LE..0001 .AND. (XL-XTP) .LE. .0001)
     $GO TO 25
   26 YL=RAD-YTP
      XL=YL/T
      YL=RAD-YL
      XL=RAD+XL
      J1=2
      IF((XT-XL) .LE..0001 .AND. (XL-XTP) .LF. .0001)
     $GO TO 25
   27 XL=XT-RAD
      YL=XL*T
      XL=XL+RAD
      YL=RAD-YL
      J1=3
      IF ((YT-YL) .LE. .0001 .AND. (YL-YTP) .LE. .0001)
     $GO TO 25
   28 XL=XTP-RAD
      YL=XL*T
      XL=XL+RAD
      YL=RAD-YL
      J1=4
      IF ((YT-YL) .LE. .0001 .AND. (YL-YTP) .LE. .0001)
     $GO TO 25
   37 WRITE (6,120) I,J,ALPHA,X,Y
  120 FORMAT(10X,'PROGRAM FAILURE AT I=',I5,3X,'J=',I5,3X
     $,'ALPHA=',F6.2,5X,'X= ',F6.2,5X,'Y= ',F6.2)
      STOP
   25 II=II+1
      IF (J1.LE. 2) GO TO 34
```

```
      I1=XL+.02
      I1=I1/ISPACE+1
      I0=YL+.02
      I0=I0/ISPACE+1
      I3=I1
      I2=I0+1
      D=YL-YT
      GO TO 35
   34 I1=XL+.02
      I1=I1/ISPACE+1
      I0=YL+.02
      I0=I0/ISPACE+1
      I3=I1+1
      I2=I0
      D=XL-XT
   35 GO TO (29,30),II
   29 X1=XL
      Y1=YL
      D1=D
      I4=I0
      I5=I1
      I6=I2
      I7=I3
   36 GO TO (26,27,28,37),J1
   30 X2=XL
      Y2=YL
      D2=D
      IF (ABS(X1-X2) .GE. .01 .OR . ABS(Y1-Y2) .GE. .01)
     $GO TO 31
      II=II-1
      GO TO 36
   31 F1=0.
      F2=0.
      OUT = -5.0
      IF(X .LE. OUT .OR. Y .LE. OUT) GO TO 42
      IF ((I4.LE. N.AND. I4.GE. 1) .AND. (I5 .LE.N .AND.
     $I5 .GE. 1)) F1=C(I4,I5)
      IF ((I6.LE. N.AND. I6.GE. 1) .AND. (I7 .LE.N .AND.
     $I7 .GE. 1)) F2=C(I6,I7)
   42 V1=F1+(D1/SPACE)*(F2-F1)
      F1=0.
      F2=0.
      IF(X .LE. OUT .OR. Y .LE. OUT) GO TO 43
      IF ((I0.LE. N.AND. I0.GE. 1) .AND. (I1 .LE.N .AND.
     $I1 .GE. 1)) F1=C(I0,I1)
      IF ((I2.LE. N.AND. I2.GE. 1) .AND. (I3 .LE.N .AND.
     $I3 .GE. 1)) F2=C(I2,I3)
   43 V2=F1+(D2/SPACE)*(F2-F1)
      D=SQRT((X-X1)**2+(Y-Y1)**2)
      DT=SQRT((X2-X1)**2+(Y2-Y1)**2)
   44 CR(I,J)=V1+(D/DT)*(V2-V1)
      GO TO 4
    6 CR(I,J)=C(I,J)
      GOTO 4
   11 JY=Y/SPACE
      D=Y-FLOAT(JY)*SPACE
      JY=JY+1
```

```
      JY1=JY+1
      CR(I,J)=C(ND,JY)+D/SPACE*(C(ND,JY1)-C(ND,JY))
    4 CONTINUE
 2010 CONTINUE
      WRITE(F,2038) ITEST,WNSPED,REQDIR,WINWT(IKE)
 2038 FORMAT(6X,'TEST NO.',I5,5X,'WIND SPEED=',F5.1,'MPH.'
     $,5X,'WIND ANGLE',F7.2,5X,'RELATIVE WEIGHT',F6.3/)
      DO 2049 I = 1, N
      DO 2048 J = 1,N
      IF(SYN .LT. 0.9) GO TO 2046
      CSN(I,J) = CR(I,J)*WINWT(IKE) + CSN(I,J)
      C(I,J) = CSN(I,J)
      IF (SYN . GT. 1.9) ICOUNT= -1
      IF((SYN .GT. 0.9).AND.(ICOUNT .EQ. -1))GO TO 2048
      IF((SYN .GT. 0.9).AND.(ICOUNT .GE. 0)) GO TO 2046
      IF(SYN .GT. 1.1) GO TO 2048
 2046 WTCC(I,J) = CR(I,J)*WINWT(IKE)+WTCC(I,J)
      CR(I,J) = WTCC(I,J)
 2048 CONTINUE
      IF(SYN .GT. 1.1) GO TO 777
      IF((ICOUNT + 1).LT.NDIR) GO TO 103
 2044 CONTINUE
C     OUTPUT OF ROTATED STACKED PATTERN
      DO 2039 I=1,N
 2039 WRITE(6,105) (CR (I,J),J=1,N)
105   FORMAT(/,5X,24F5.1)
C
C     SHIFT IN CENTER OF MASS AND RESULTANT VELOCITY
C            VECTOR CALCULATION
C
 2041 XS=0.
      XM=0.
      YS=0.
      YM=0.
      DO 1 I=1,N
      DO 1 J=1,N
 2043 CC = CR(I,J)
      XM=XM+SPACE*FLOAT(J  )*CC
      YM=YM+SPACE*FLOAT(I  )*CC
      XS=XS+CC
    1 YS=YS+CC
      XC=XM/XS
      YC=YM/YS
      IF (IT .LT. 0) XG=FLOAT(N/2+1)*SPACE
      IF (IT .EQ. 0) XG=(FLOAT((N/2)+0.5))*SPACE
      YG=XG
      XD=XG-XC
      YD=YG-YC
      ALPHA=ATAN2(YD,XD)
      ALPHA=ALPHA*57.296-90.
      D=SQRT(XD**2+YD**2)
      RESANG=ATAN2(YCOR,XCOR)
      RESANG=RESANG*57.29578
      RESVEL=SQRT(YCOR**2+XCOR**2)
C
C     CALCULATION OF INTERMEDIATE GRID POINTS BY LINEAR
C        INTERPOLATION
```

```
      L=(SPACE+.02)/S2
      IF(L.EQ.1) GO TO 804
      L1=L-1
      N1=N-1
      DO 800 I=1,N
      DO 800 J=1,N1
      F1=CR(I,J)
      F2=CR(I,J+1)
      I1=L*(I-1)+1
      J1=L*(J-1)+1
      CE(I1,J1) = CR(I,J)
      CE(I1,J1+L)=CR(I,J+1)
      DO 801 K=1,L1
 801  CE(I1,J1+K)=F1+FLOAT(K)/FLOAT(L)*(F2-F1)
 800  CONTINUE
      NN=L*(N-1)+1
      N4=NN-L
      DO 803 I=1,N4,L
      DO 803 J=1,NN
      F1=CE(I,J)
      F2=CE(I+L,J)
      DO 802 K=1,L1
 802  CE(I+K,J)=F1+FLOAT(K)/FLOAT(L)*(F2-F1)
 803  CONTINUE
C
C     SUPERIMPOSITION OF SPRINKLER PATTERN AND
C        CALCULATION OF UNIFORMITY COEFFICIENT
C
      ND=NN/2+1
 804  DO 64 M=1,NSR
      LS=ILS(M)
      MS=IMS(M)
      LS1 = LS + ND
      DO 51 J = ND,LS1
      JJ=J
      IF(JJ.LE.NN) GO TO 88
 89   JJ=JJ-LS
      IF(JJ.GT.NN) GO TO 89
 88   I1=JJ
      I2=JJ
      I3=J-ND+1
      DO 56 I=1,NN
 56   A(I,I3)=CE(I,JJ)
 53   I1=I1+LS
      I2=I2-LS
      IF(I1.GT.NN) GO TO 50
      DO 54 I=1,NN
 54   A(I,I3)=A(I,I3)+CE(I,I1)
 50   IF(I2.LT.1) GO TO 51
      DO 55 I=1,NN
 55   A(I,I3)=A(I,I3)+CE(I,I2)
      GO TO 53
 51   CONTINUE
      MS1=MS+ND
      LS2=LS+1
      DO 57 I=ND,MS1
```

```
      IIJ=I
      IF(IIJ.LE.NN) GO TO 90
91    IIJ=IIJ-MS
      IF(IIJ.GT.NN) GO TO 91
90    J1=IIJ
      J2=IIJ
      I3=I-ND+1
      DO 60 II=1,LS2
60    B(I3,II)=A(IIJ,II)
67    J1=J1+MS
      J2=J2-MS
      IF(J1.GT.NN) GO TO 58
      DO 61 II=1,LS2
61    B(I3,II)=B(I3,II)+A(J1,II)
58    IF(J2.LT.1) GO TO 57
      DO 63 II=1,LS2
63    B(I3,II)=B(I3,II)+A(J2,II)
      GO TO 67
57    CONTINUE
      MS2=MS+1
      SUM=0.
      DO 65 I=1,MS2
      DO 65 J=1,LS2
65    SUM=SUM+B(I,J)
      AVG =SUM/FLOAT(LS2*MS2)
      SD=0.
      DO 66 I=1,MS2
      DO 66 J=1,LS2
      DEV = ABS(B(I,J)-AVG)
66    SD=SD+DEV
      CU=100.*(1.-SD/SUM)
      AMS=SM(M)*DIA
      ALS=SL(M)*DIA
      SR=ALS/AMS
      WRITE(6,2020) SL(M),SM(M),SR,CU
2020  FORMAT(5X,'LAT SPACE',F5.2,5X,'M SPACE',
     $F5.2,5X,'SR',F5.2,5X,'CU',F6.1)
64    CONTINUE
      WRITE(6,2021) D,ALPHA,RESVEL,RESANG
2021  FORMAT(5X,'CENTER OF MASS SHIFT',10X,F7.2,
     $5X,'SHIFT ANGLE',F7.2/,5X,'RESULTANT WIND VECTOR'
     $,9X,F7.2,5X,'ANGLE',6X,F7.2)
      GO TO 2
3     STOP
      END

                   NO  DIAGNOSTICS.
```

Appendix C

Uniformity Values for Stacked and Median Angle Patterns at Several Wind Speeds

Uniformity values for stacked and median angle patterns under several wind speeds for three spacings (feet).

Angle of contributing elements[a]	Uniformity coefficient values						Ave. difference[b]
	Stacked pattern			Median angle pattern			
	30x40	30x50	40x50	30x40	30x50	40x50	
- - - - - - - - - - - - - - Wind speed 2.0 mph - - - - - - - - - - - - - -							
0 and 10	90.9	89.4	88.3	91.0	89.3	88.3	0.1
0 to 20	90.9	89.1	88.1	91.1	89.0	88.1	0.1
0 to 30	90.9	88.8	87.9	91.3	88.6	88.0	0.3
0 to 40	90.9	88.7	87.7	90.9	88.2	87.6	0.2
0 to 50	90.9	88.6	87.5	91.1	88.2	87.4	0.2
0 to 60	91.0	88.5	87.4	90.6	87.8	87.1	0.5
0 to 70	91.0	88.3	87.1	90.9	87.8	87.2	0.2
0 to 80	91.0	88.2	86.9	90.9	87.7	87.0	0.2
0 to 90	91.1	88.2	86.9	90.9	87.6	86.8	0.3
- - - - - - - - - - - - - - Wind speed 2.1 mph - - - - - - - - - - - - - -							
0 and 10	94.4	91.1	90.0	94.2	91.2	90.0	0.1
0 to 20	94.6	91.4	90.1	94.4	91.0	89.9	0.3
0 to 30	95.0	91.4	90.0	94.8	91.7	90.4	0.3
0 to 40	95.5	91.2	89.8	94.8	91.4	89.9	0.3
0 to 50	95.8	91.0	89.7	95.3	91.2	89.5	0.3
0 to 60	96.1	90.6	89.5	95.8	91.1	89.3	0.3
0 to 70	96.5	90.1	89.2	96.4	90.8	88.8	0.4
0 to 80	96.8	89.7	89.1	96.9	90.3	88.4	0.5
0 to 90	97.1	89.4	88.9	96.7	90.1	88.5	0.5

Uniformity values for stacked and median angle patterns under several wind speeds for three spacings (feet). (Continued)

Angle of contributing elements^a	Uniformity coefficient values						Ave. difference^b
	Stacked pattern			Median angle pattern			
	30x40	30x50	40x50	30x40	30x50	40x50	
Wind speed = 3.8 mph							
0 and 10	94.8	91.8	89.1	94.8	91.8	89.2	0.0
0 to 20	94.7	91.5	89.1	94.5	91.4	88.5	0.3
0 to 30	94.6	91.4	89.3	94.2	91.0	88.0	0.7
0 to 40	94.6	91.5	89.6	94.2	90.7	88.1	0.9
0 to 50	94.7	91.7	90.2	94.0	90.8	88.7	1.1
0 to 60	94.7	92.0	90.7	94.1	90.9	89.0	1.1
0 to 70	94.7	92.1	91.2	94.1	91.2	89.7	1.0
0 to 80	94.6	92.4	91.6	93.6	91.0	89.8	1.4
0 to 90	94.6	92.7	92.1	93.9	91.5	90.1	1.3
Wind speed = 4.0 mph							
0 and 10	91.2	89.8	90.0	90.6	89.8	90.3	0.3
0 to 20	92.0	89.4	89.5	91.6	89.3	89.4	0.3
0 to 30	92.7	89.0	89.1	92.6	88.9	88.9	0.1
0 to 40	93.4	88.6	88.7	92.6	88.0	87.8	0.8
0 to 50	94.0	88.6	88.7	93.0	87.6	87.2	1.2
0 to 60	94.5	88.6	88.7	94.1	87.2	87.4	1.1
0 to 70	95.0	88.8	88.8	94.1	86.8	86.9	1.6
0 to 80	95.5	88.9	88.8	95.0	86.2	85.9	2.0
0 to 90	95.9	89.1	88.8	95.7	86.8	86.1	1.7

Uniformity values for stacked and median angle patterns under several wind speeds for three spacing (feet). (Continued)

Angle of contributing elements[a]	Uniformity coefficient values						Ave. difference[b]
	Stacked pattern			Median angle pattern			
	30x40	30x50	40x50	30x40	30x50	40x50	
Wind speed = 5.7 mph							
0 and 10	91.0	87.8	83.2	91.0	87.9	83.0	0.1
0 to 20	91.4	88.7	84.3	90.9	88.4	83.6	0.5
0 to 30	91.7	89.4	85.4	91.1	89.2	84.4	0.5
0 to 40	91.9	90.1	86.7	91.6	89.8	85.2	0.7
0 to 50	92.1	90.8	88.0	91.4	90.2	86.1	0.9
0 to 60	92.6	91.6	89.3	91.6	90.5	86.7	1.6
0 to 70	93.0	92.3	90.5	91.6	91.0	87.4	1.9
0 to 80	93.3	93.0	91.4	91.0	91.7	88.2	2.3
0 to 90	93.7	93.6	92.2	90.6	92.0	88.2	2.9
Wind speed = 5.9 mph							
0 and 10	91.3	87.2	75.5	91.3	87.0	75.4	0.1
0 to 20	91.6	87.4	75.8	91.4	86.9	75.7	0.6
0 to 30	91.5	87.6	[illegible]	91.0	87.0	76.6	0.9
0 to 40	91.6	87.9	79.9	91.0	87.5	77.3	1.2
0 to 50	91.5	88.3	81.5	90.2	87.2	77.9	2.0
0 to 60	91.3	88.8	83.1	89.7	87.2	78.6	2.5
0 to 70	90.8	89.2	84.6	89.4	87.4	80.2	2.5
0 to 80	90.5	89.7	85.9	88.9	86.9	80.6	3.2
0 to 90	90.2	90.3	86.9	87.7	86.3	81.6	3.9

Uniformity values for stacked and median angle patterns under several wind speeds for three spacings (feet). (Continued)

Angle of contributing elements[a]	Uniformity coefficient values						Ave. difference
	Stacked pattern			Median angle pattern			
	30x40	30x50	40x50	30x40	30x50	40x50	
Wind speed = 7.7 mph							
0 and 10	85.6	87.0	73.4	85.0	86.2	72.2	0.9
0 to 20	85.6	86.8	73.8	84.6	85.7	71.8	1.4
0 to 30	85.6	86.9	74.8	84.0	85.5	71.6	2.1
0 to 40	85.5	87.2	76.2	83.6	85.0	71.4	3.0
0 to 50	85.6	87.6	77.6	83.6	85.0	71.1	3.7
0 to 60	85.8	88.2	79.5	83.5	84.7	71.2	4.7
0 to 70	86.2	89.1	81.7	83.0	84.4	71.0	6.2
0 to 80	86.8	89.9	83.7	83.1	84.8	71.3	7.1
0 to 90	87.7	90.7	85.8	82.5	85.4	71.6	8.2
Wind speed = 7.9 mph							
0 and 10	83.4	81.9	72.9	83.3	81.9	72.4	0.2
0 to 20	83.8	82.5	74.0	83.6	82.2	72.7	0.6
0 to 30	84.6	83.7	75.9	83.6	82.5	72.9	1.7
0 to 40	85.7	85.1	78.4	83.9	83.0	74.0	2.8
0 to 50	87.0	86.7	80.8	84.3	84.0	75.4	3.6
0 to 60	88.4	88.1	83.2	84.8	85.4	77.0	4.2
0 to 70	89.9	89.5	85.5	84.6	86.0	77.6	5.6
0 to 80	91.0	90.7	87.4	84.9	86.6	78.2	6.5
0 to 90	91.9	91.8	89.0	84.4	86.3	78.3	7.9

Uniformity values for stacked and median angle patterns under several wind speeds for three spacings (feet). (Continued)

Angle of contributing elements[a]	Uniformity coefficient values						Ave. difference[b]
	Stacked pattern			Median angle pattern			
	30x40	30x50	40x50	30x40	30x50	40x50	
Wind speed = 9.4 mph							
0 and 10	90.7	81.5	77.8	90.6	82.0	77.9	0.1
0 to 20	90.8	81.5	78.7	90.2	81.0	77.7	0.7
0 to 30	91.5	82.0	80.0	91.2	81.7	78.7	0.7
0 to 40	92.4	82.6	81.3	90.9	81.3	78.9	1.7
0 to 50	93.0	83.6	82.8	91.5	82.1	80.0	1.9
0 to 60	93.3	84.9	84.3	91.8	81.9	80.5	2.8
0 to 70	93.8	86.2	85.8	91.4	81.5	80.7	4.1
0 to 80	94.7	87.7	87.3	88.9	80.6	79.9	6.8
0 to 90	95.5	89.5	89.1	88.5	80.9	79.7	8.3
Wind speed = 11.3 mph							
0 and 10	79.4	76.3	74.0	78.2	75.3	72.7	1.2
0 to 20	81.1	78.2	75.5	79.2	76.3	73.0	2.1
0 to 30	83.3	80.3	77.8	80.1	77.2	73.2	3.6
0 to 40	85.9	82.7	80.4	81.5	78.7	74.1	4.9
0 to 50	88.4	85.1	83.1	81.9	79.7	74.5	6.8
0 to 60	91.0	87.1	85.6	82.9	81.2	75.6	8.0
0 to 70	93.2	88.5	87.7	84.0	82.8	76.4	8.7
0 to 80	95.0	89.6	89.3	85.0	84.2	76.9	9.3
0 to 90	95.8	90.5	90.2	86.1	85.6	77.4	9.1

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[a] The range of pattern rotation is given, e.g., 0 to 30 means a stacked pattern containing 0, 10, 20, and 30 degree rotated patterns.

[b] This is the average of the absolute difference between the stacked and median angle pattern UC values.

VITA

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