EFFECT OF WIND SPEED ON SPRINKLER PERFORMANCE IN THE BEKAA PLAIN

by

Ismail Yusuf Mutayrah

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I. Yusuf Mutayrah

ABSTRACT

The effect of the winds commonly occurring in the Bekaa on the performance of sprinklers was evaluated first in terms of its influence on the uniformity coefficient and water application efficiency, and second in terms of water, labor, and equipment requirements. Reductions in uniformity coefficient and water application efficiency were produced under high winds. To attain higher uniformity coefficients under high wind conditions closer spacings should be selected. A 12 x 12 meter spacing was found best suited under the typical average low wind conditions, while an 8 x 10 meter spacing was found best suited under the typical high wind conditions.

A water application efficiency of 62.5% was attained under low winds while 55.10% was attained under high winds.

The equipment, labor, and water requirements of the four possible alternative practices for reducing the effect of wind while using the same type of sprinkler head and operating pressure were determined. These were compared with the requirements under conditions of no wind. These comparisons showed an increase of 10 to 20% in equipment requirements and a decrease of 6.6 to 9.1% in efficiency. Labor requirements showed an increase of 20% for one alternative only. The hours of daily operation showed a reduction ranging from 17

to 9%.

A comprehensive economical evaluation of the above alternatives is recommended.

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INTRODUCTION

Sprinkler irrigation is one of the important methods of irrigation used all over the world. It has been recently developed, but it is rapidly growing especially in areas of limited water supply, or where land grading for surface methods is not practical. The main characteristics of sprinkler irrigation which are often considered as advantages, are high efficiency and uniformity of water application(9). However, in many cases it has been found difficult to achieve these. The main factor that limits the achievement of high efficiency and uniform water distribution, and which has not yet been overcome, is the presence of daily wind variations. There has been little work done on the effect of this variation on the uniformity coefficient of sprinklers.

In the Bekaa Plain of Lebanon, sprinkler irrigation was introduced during the last ten years but mainly for experimental work. Extensive use of sprinklers by the farmers in the Bekaa can be expected if it can be proven that sprinkler irrigation is more efficient and more economical than other methods of irrigation. The achievement of high efficiency and uniform water application by sprinklers is limited by the presence of a wind problem in the area. The daily wind variations in the Bekaa are considered as a major factor affecting the possibility of sprinkler expansion. Occurrence of irregular strong winds distorts the uniformity of water application and may increase the drift losses appreciably.

To solve the problem of high wind, it has been recommended by few workers - especially sprinkler manufacturers - that the spacing between sprinklers should be reduced and the laterals should be placed across the path of the wind. However to determine to what extent farmers can decrease these spacings and retain a high efficiency of distribution as reflected by suitable economic measures is a problem that has not been solved yet. Nor is it reasonable to expect a general solution that could be applied under all circumstances. A complete study of each specific situation is necessary to evaluate the wind effect and to draw practical conclusions.

The present work has been conducted as an attempt to evaluate the effect of winds commonly occurring in the Bekaa on the performance of sprinklers. The main concern in this study is the physical effect of wind on the water application efficiency and uniformity coefficient of sprinklers. Possible engineering designs to meet the wind conditions in the Bekaa Plain will be presented and evaluated. The ultimate purpose this study would serve would be to determine the increased cost in sprinkler irrigation caused by the daily wind variations commonly occurring in the Bekaa.

REVIEW OF LITERATURE

Evaluation of the performance of sprinkler irrigation depends mainly upon the determination of the uniformity coefficient, and of the water application efficiency(10). Lack of uniformity of water distribution is the first major problem to be solved. If the distribution is not uniform it means the soil is wetted in an irregular manner, and therefore the efficiency of water application is impaired. The normal procedure for insuring high efficiency and high uniformity coefficient is the proper design of the sprinkler irrigation system. One of the most important preliminary design factors is the wind. It is the purpose of this section to review the available information pertaining to the effect of wind on the uniformity coefficient and water application efficiency of sprinklers and the measures recommended for reducing such effects.

Uniformity Coefficient

The distribution of water from a single rotating sprinkler is not uniform over the entire wetted circle. Under low or no wind conditions, the greatest depth of application occurs around the sprinkler and decreases with distance radially outwards. Therefore, it is necessary to space sprinklers closer than the diameter of their wetted circles in order to give an overlapping pattern resulting with approximately the same amount of water applied all over the irrigated area(18).

McCulloch(17) stated in a design procedure for sprinkler irrigation that for each type of sprinkler head operating under a fixed pressure, there is a characteristic distribution pattern with a certain diameter of coverage. This pattern is completely changed by high wind movement. He concluded that in windy areas, it is important to allow for this change by reducing the lateral spacing, or by using triangular rather than rectangular spacing arrangements.

Lewis(15) found in his study on sprinkler and other methods of irrigation that the main factor that causes non-uniform water application by sprinklers, and which changes the sprinkler distribution pattern, is high wind movement.

Powers and Bertramson(23) presented the results of a study on low pressure sprinkler systems including the RainBird sprinkler. At little or no wind, they found that, for these low pressure sprinklers, a 60-by 60-foot square or triangular spacing applied the water more uniformly than the 40-by 60 -foot rectangular spacing.

Scott(26) stated that one of the biggest difficulties in obtaining a uniform water distribution from the sprinklers is wind. Under high wind, parts of the area irrigated by sprinklers may be dry. He reported that in some cases operations of sprinklers have been shut down when wind conditions created serious distortions. To overcome the wind effect, he suggested changes in sprinkler nozzles, in the spacing of sprinklers and laterals, and in arrangements. However these changes, he added, mean additional equipment and labor, thus, extra cost. He concluded that if wind conditions are a problem, they should be considered in the original design of the sprinkler system, and a closer spacing should be provided.

Bauzil(3) reported that a triangular spacing equal to 55 to 60 percent of the wetted diameter of the sprinkler would generally give a superior uniformity of distribution over that of a square spacing. Also Selim and Nicola(27) reported that equilateral triangular spacing equal to 60 percent of the wetted diameter was used to overcome the wind effect.

Quackenbush and Shockley(25) listed wind as one of the main limitations for sprinkler use. They reported that wind distorts the sprinkler patterns and causes an uneven distribution of water. They recommended an adjustment of sprinkler and lateral spacings to solve the problem of high wind. Also Thorne and Peterson(30), and Israelson(12) considered wind as a limiting factor affecting the uniform water distribution from the sprinkler and recommended the use of closer spacings to relieve such effect.

Abd El-Samie(1) reported from a study on the efficiency of sprinkler irrigation in the Desert Soil Reclamation Project at Inchass , Egypt that one of the purposes of establishing wind breaks was to eliminate the effect of wind on the uniformity of water distribution from the sprinklers.

Christiansen(13), from 1940-1942, made an extensive study on the uniformity of water application by several commercial sprinklers. He developed the formula known by his name for calculating the uniformity coefficient. Expressed as a percentage, it is:

$$UCc = 100 \left[1 - \frac{|x_i - \bar{x}|}{n\bar{x}} \right]$$

in which UCc is the Christiansen uniformity coefficient, $|x_i - \bar{x}|$ is the sum of the absolute deviations of individual observations (X_i) from the average of all observations$(\bar{X})$, and n is the number of observations. Using this formula, he studied the effect of wind, speed of rotation, and spacing of sprinklers upon the water distribution. His conclusion on the effect of wind was that, although the distribution patterns appeared very uneven, the effect of wind on the uniformity of distribution was reduced over a larger area, and with sprinklers close enough together to provide an adequate overlap.

In 1947, Wilcox and Swailes(31) reported the results of a study on the uniformity of water distribution by some undertree orchard sprinklers. The purpose of their study was to compare the distribution pattern of the common sprinklers at various pressures and spacings. They conducted all their experimental trials at little or no wind. They calculated the uniformity coefficient in a similar manner to that used by Christiansen, except that the squares of the deviations from the mean were used rather than the deviations themselves. The equation used was as follows:

$$U = 100 - \frac{100SD}{M}$$

in which U = uniformity coefficient, SD = the standard deviation of the total depths of water, and M = the mean of these depths. This modified equation of Christiansen lays special stress on extreme values. The uniformity coefficients obtained by this equation are not as high as those obtained when deviations from the mean are used as a basis. A value of 100 represents perfect uniformity, and a value lower than this means less uniformity. By using this method of calculation, very low or even below zero values might result, which is not convenient for evaluation. They concluded from their results that at high pressures and with spacing kept constant, the distribution was much more uniform, but there was a tendency for the water to be thrown higher in the air as the pressure was increased. With an increase of pressure, also, the water drops became smaller. For both of these reasons, the spray was more easily blown aside by the wind at the higher pressures. An increase of distance of spacing was accompanied by a general decrease in the uniformity coefficient in almost every case. The square spacing was found to produce higher uniformity than rectangular spacing, when similar areas were compared.

Korven(13), in 1951, conducted a study on the effect of wind on the uniformity of water distribution by some rotary sprinklers. He reported that the irregular patterns that were shown by drawing depth of water application contours depicted the erratic water distribution when sprinkling during periods of high winds. The calculated coefficient of uniformity decreased as the wind speed increased. The average uniformity coefficient at a wind speed of 0 to 4 miles per hour and a spacing of 50 x 50 foot was about 82, and at 17 miles per hour and the same spacing was about 33. It was also noted that during calm periods all the sprinklers investigated gave very similar coefficients at the recommended spacings. He found out that a relatively high degree of uniformity was produced when the sprinkler lines were placed across the path of the wind.

Tests of various sprinkler spacings under different wind conditions, and the drawing of distribution curves together with field observation were carried out by the RainBird Sprinkler Manufacturing Corporation(8). The following spacings between sprinklers and laterals, according to wind velocities, were recommended:

Average wind speed	Recommended spacing in percent of wetted diameter
No wind	65
Up to 4 M.P.H.	60
Up to 8 M.P.H.	50
Above 8 M.P.H.	30

Water Application Efficiency

Water application efficiency has been defined by the Committee on Irrigation of the American Society of Agricultural Engineers as the percentage of the water applied that can be accounted for as an increase in soil moisture in the soil occupied by the principal rooting system of the crop. It is expressed in the following formula:

$$Ea = \left(\frac{Ws}{Wf} \right) 100$$

where Ea is the water application efficiency, Ws is the amount of water stored in the root zone during the irrigation, and Wf is the amount of water delivered from the sprinkler nozzles in case of sprinkler irrigation(28).

Myers and Haise(20) and Kruse, et. al.,(14) considered water application efficiency as a basis for evaluating both sprinkler and surface methods of irrigation. They defined water application efficiency as the percentage ratio between the quantity of water stored in the soil in the crop rootzone and the quantity of water applied to the field. In case of sprinkler irrigation the water application efficiency is actually determined by that percentage of the applied water which is lost through evaporation and drift from the spray, through percolation beyond the rootzone, and through runoff from the irrigated field.

Frost and Schwalen(6) conducted a study on spray losses in sprinkler irrigation to determine the percent of water reaching the ground during application. It is reported by them that results of previous work on the determination of evaporation losses from sprinkler spray indicate that application efficiencies would be extremely low at high wind velocities, high temperature, and low humidity. Some of their tests were run at 8 to 10 miles per hour wind velocity for comparison with those at 0 to 5 miles per hour. The spray losses were considerably higher at the high wind velocity as much of the fine spray was carried out of the collecting area. Doubling the wind velocity approximately doubled the losses. They concluded that the losses occuring to the water drops when they leave the sprinkler nozzles until they hit the ground surface are:

1. Evaporation losses
2. Drift losses which are small droplets carried by the wind.

High wind was found to increase both losses.

Somerhalder(18) reported that sprinkler tests in Arizona showed that losses due to evaporation of the spray on a hot day, and due to wind drift, reached 30% of the applied water. Consequently the water application efficiency was reduced by 30%.

From the above review, it is clearly shown that all the work carried out on wind effect on sprinklers treated the problem in a general way. In order to solve the problem of wind effect, investigation of each specific condition should be done. Peikert(22) stated that "in order to utilize sprinkler irrigation to the fullest advantage, research programs should be established on spacings of sprinklers, wind velocity effect, and evaporation losses."

MATERIALS AND METHODS

The field tests for this study were conducted at the Agricultural Research and Educational Center, between September 21 and October 2, 1962. The Center is located in the Bekaa Plain of Lebanon, about 1000 meters above sea level. The Plain is considered the most important agricultural area in Lebanon.

The experimental design was based on operating a single sprinkler, under a fixed pressure, during periods of varying wind conditions, that exist in the Bekaa. The effect of wind was evaluated through the determination of the actual water distribution pattern under different wind conditions. Spray cans were distributed over a square grid system laid around the sprinkler. The water distribution patterns were used to express the effect of wind in terms of its influence on the uniformity coefficient and water application efficiency.

The experimental layout is shown in figure 1. Water was pumped from a surface reservoir with a centrifugal pump driven by an electric motor. A pressure gage, reading from 0 to 100 pounds per square inch, was attached to the system. Another pressure gage with a pitot-tube attachment was used to measure the pressure at the sprinkler nozzle. Valves A and B were designed to control the pressure at the pressure gage and the sprinkler head. Valve A was fixed to a return pipe to regulate the flow of excess water coming back to the reservoir. Valve B was attached to the main line to regulate the flow toward the sprinkler head. The main pipe line and the return-pipe were aluminum pipes with rubber gasket couplings. No change in layout was introduced during the time the experiments were run.

A slow revolving sprinkler was used in the experiment with the following specifications:

Name of manufacturer:		RainBird Sprinkler Manufacturing Corporation, Glendora, California
Model	:	30
Number of nozzles	:	2
Nozzle sizes		3/16" and 3/32" angle 7°.
Rated discharge	:	8.07 gpm at 40 psi

Spray cans, 7.5 cms. in diameter and 5.5 cms. deep, were distributed in a 2 meter square grid pattern. The sprinkler was placed in the center. The cans were set level and firmed in the soil so as not to overturn. The cans were distributed over an area larger than that covered by the sprinkler under all wind conditions.

During the summer months on the A.R.E. Center, daily wind variations were studied and the following general pattern was observed. Low winds with velocities ranging from 0 to 10 kilometers per hour prevail from early morning till noon. Around noon strong winds with varying intensities start blowing until 5 or 6 p.m. and occasionally continue into the early hours of the night. Based on this

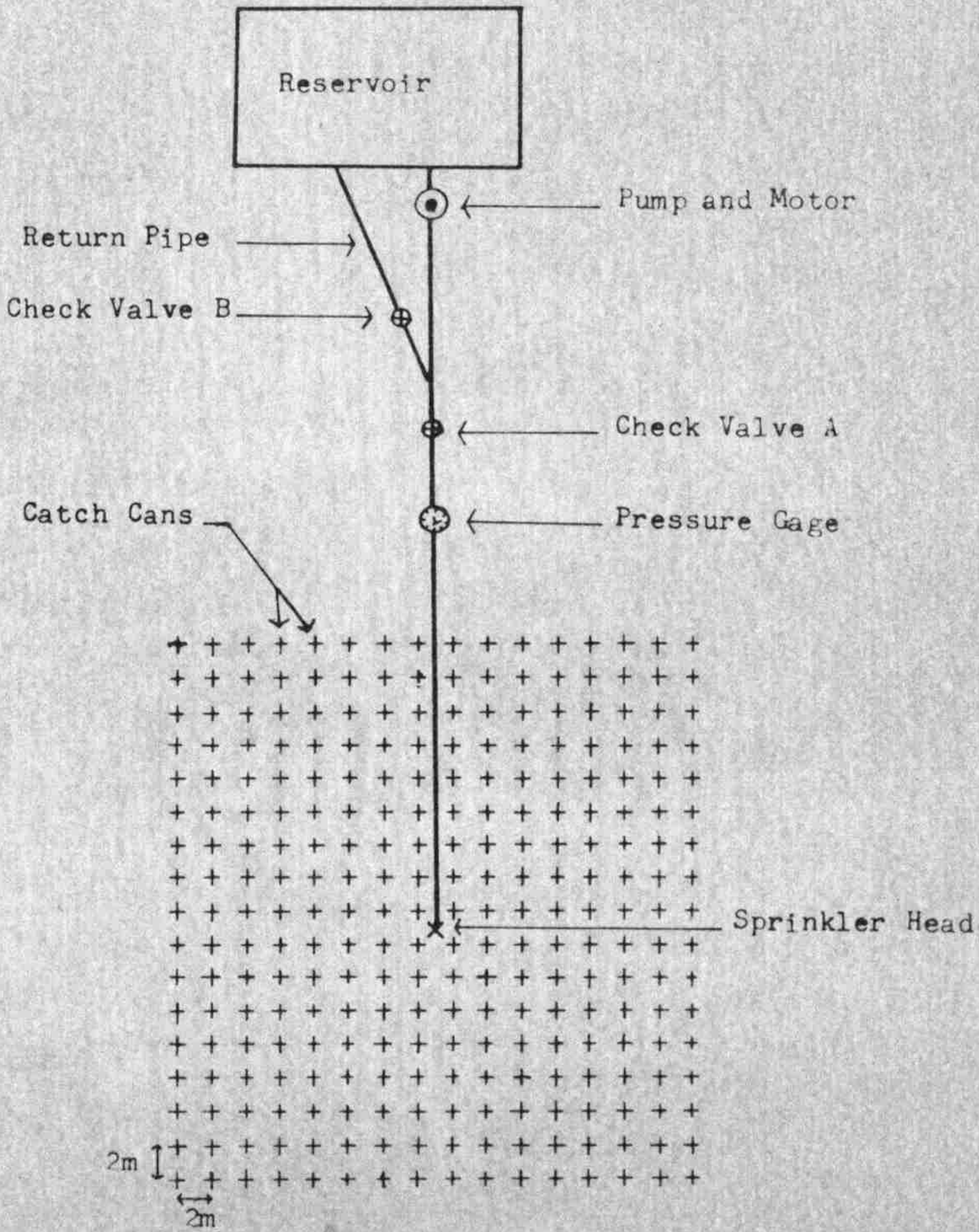

Figure 1. Experimental layout

pattern or trend of wind variation the experimental trials were divided into two groups, one carried out during the low wind period which was during the mornings, and the other during high wind period which was during the after noons. The duration of each trial was not the same. It varied between 2 and 4 hours.

The sprinkler was operated at a constant pressure of 40 pounds per square inch(psi) at the sprinkler nozzles, measured by a pressure gage with a pitot-tube attachment. This pressure was maintained as such through maintaining the pressure at the pressure gage, near the pump, at 40.8 pounds per square inch. The loss of 0.8 pounds pressure between the pressure gage and the sprinkler head was due to friction in the pipe. Whenever an increase of pressure was noticed at the pressure gage the flow toward the sprinkler was reduced while that toward the reservoir was increased by means of valves A and B until the pressure was retained constant.

Before running the experimental trials the sprinkler was operated for checking. The flow was regulated, and the pressure at the pressure gage, and at the sprinkler head, was manipulated and fixed at the previous values.

Test runs were started in September 21. The time at the start of each test was recorded. Simultaneously, with the operation of the sprinkler, wind velocity measurements were recorded as follows. The readings of a 4-cup rotational anemometer placed 2 meters above ground level were taken every 2 minutes for 14 or 16 minutes, after which another 14 or 16 minutes were spent checking the pressure and the whole operation of the experiment. Later, the average wind speed in kilometers per hour was calculated for each 2 minutes interval by dividing the difference between eadh two successive readings over 2 minutes, and multiplying by 60.

At the end of each experimental trial, water was cut-off, and the time the sprinkler stopped operating was recorded. Wind speed observation was ended too. The water caught in the spray cans during the test run was measured by a graduated cylinder. Any amount less than 10 cubic centimeters was neglected. The figures obtained were in cubic centimeters per period of run. Later these figures were converted into depth of water in millimeters per hour by dividing them over the base area of the tin can and the number of hours the experimental test was run, and multiplying by 10 to change to millimeters.

The number of experimental trials carried out during the period from September 21 to October 2, 1962, were 16 trials. A table was made for each trial showing the amount of water received by each can within the area of wetting and at the relatige position to the sprinkler. The average wind speed for each experimental trial was calculated by averaging all the wind speeds recorded during the time of run.

The variation of wind speed under each test was stated in a range form by taking the minimum and maximum wind velocities occuring while the experiment was running.

Measurements of the sprinkler discharge at the nozzles was recorded for the calculation of the water application efficiency. The volumetric measurement of this discharge was taken by placing two rubber hoses over the nozzles and directing the flow into a graduated container. The time for filling the container to a certain amount was recorded using a stop watch. The discharge was calculated as liters per hour.

DESIGNS AND EVALUATIONS

Distribution Patterns

The experimental tests, as mentioned before in materials and methods, were carried out under different wind conditions selected on the basis of the observed pattern of wind variation in the Bekaa Plain during the irrigation season. The 16 tests performed during the experimental period depicted the actual water distribution patterns under wind conditions with velocities ranging from 0 to 37 kilometers per hour. None of the tests showed a distribution pattern of water under a fixed wind velocity, but it was apparent that most of the tests revealed the water distribution pattern under either one of two distinct wind conditions. The first was a low wind condition occuring in the mornings, and did not seem to affect the uniformity of water application from the sprinkler head. The second was a relatively high wind condition occuring in the afternoons which distorted the water distribution pattern. Out of the 16 experimental tests, 8 were selected to represent these two dominant or typical wind conditions in the Bekaa. The other 8 tests, actually, represented water distribution under a transitional wind condition - from low wind to high wind. It would have been very difficult to consider all possible wind variations because of the time limitation, and the infinite possibilities of wind fluctuations. So, stress was laid on the average wind velocities, and only the two dominant wind conditions are considered in this work. To estimate the water distribution patterns for wind velocities between low and high winds, interpolation could be used with reasonable precision.

The 4 tests selected to represent the actual water distribution obtained under low wind condition are presented in figures 2 to 5 inclusive. The figures shown are depth of application in millimeters per hour received at each catch recording can. The relative positions of the cans with respect to the sprinkler are shown according to the four points of the compass N, S, W, E. In order to illustrate the effect of wind on the water distribution, the 5, and 3 millimeters water application contour lines were drawn. The distribution patterns with the resultant water application contour lines in figures 2, 3, 4, and 5 depict the uniform water application expected from the RainBird sprinkler under no wind or average low wind conditions. The depth of water applied is greatest around the sprinkler and starts decreasing uniformly with distance from the sprinkler in all directions. The resultant water contour lines in all the figures 2, 3, 4, and 5 are more or less circular. They resemble circles with enlarging diameters,

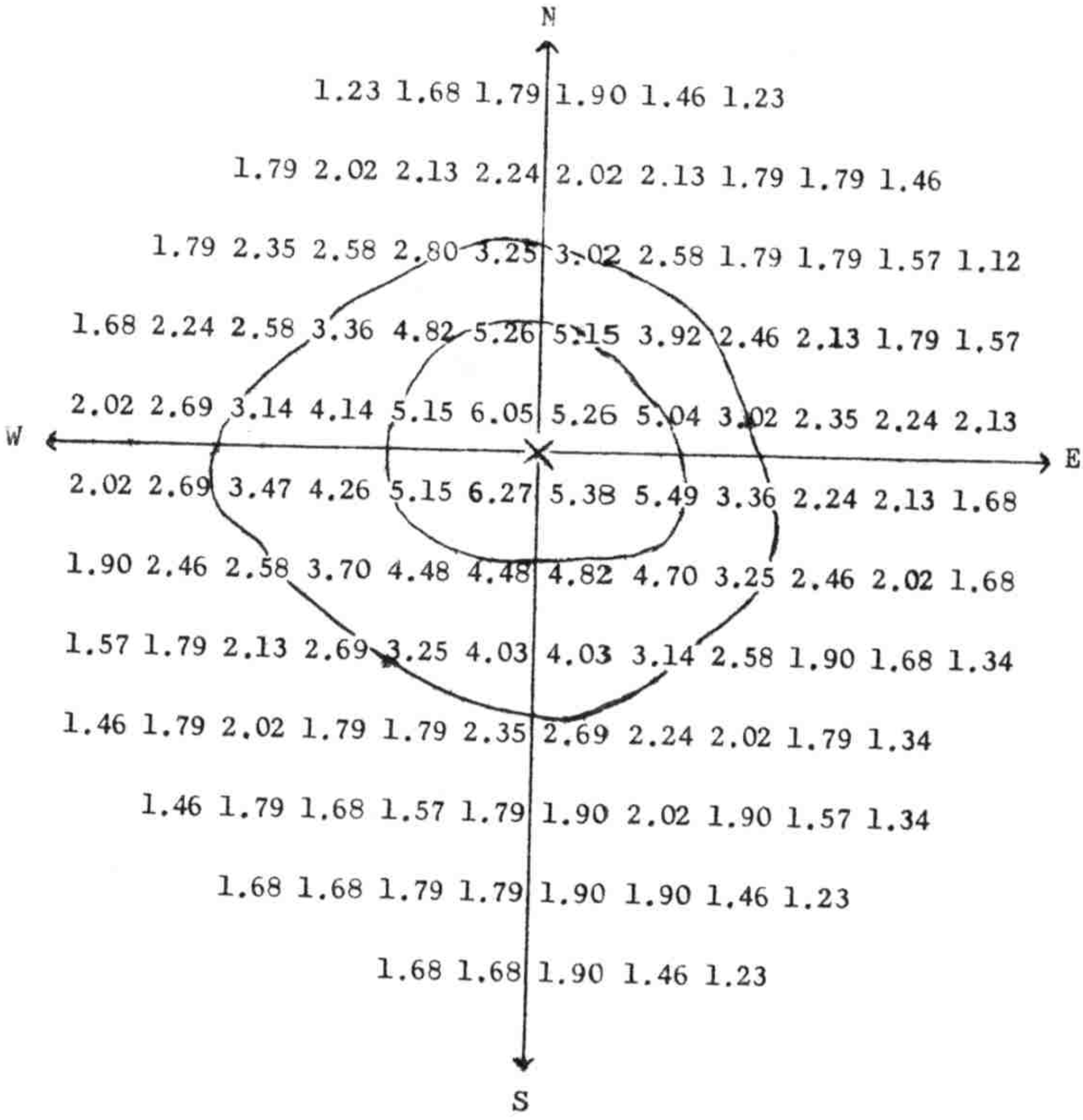

Figure 2. Water distribution pattern - Test No. 1, 7:00 AM to 9:00 AM, September 24, 1962.
Figures shown are depth of application in millimeters per hour.
X = position of sprinkler
The 3 and 5 millimeter water contours were superimposed.

Table 1. Observed wind velocities for Test No. 1.

Operating time min.	Average wind velocity km./hr.
15	
	6.0
17	
	5.4
19	
	5.1
21	
	6.3
23	
	5.4
25	
	6.0
27	
	4.8
29	
	4.8
31	
Interval average	5.5
46	
	1.8
48	
	3.9
50	
	3.6
52	
	3.0
54	
	4.5
56	
	3.9
58	
	3.0
60	
Interval average	2.4

Operating time min.	Average wind velocity km./hr.
74	
	2.1
76	
	1.8
78	
	3.3
80	
	2.1
82	
	2.7
84	
	0.9
86	
	2.1
88	
Interval average	2.1
102	
	3.9
104	
	3.9
106	
	3.3
108	
	3.0
110	
	0.9
112	
	0.6
114	
	1.2
116	
	3.6
118	
Interval average	2.6

Period average wind velocity = 3.4 km./hr.

Range = 0.6 to 6.3 km./hr.

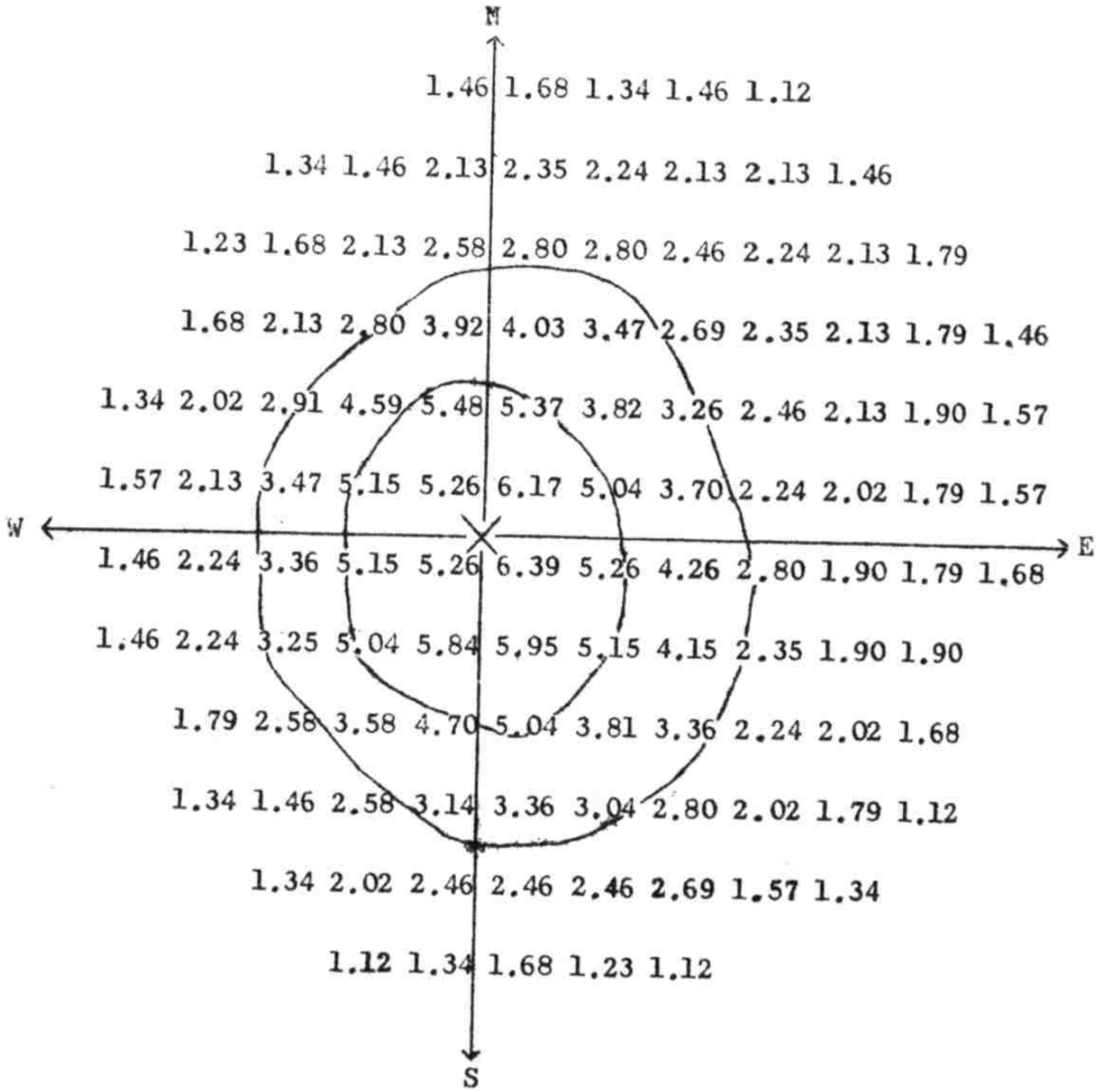

Figure 3. Water distribution pattern - Test No. 2, 7:45 AM to 9:45 AM, September 25, 1962.
Figures shown are depth of application in millimeters per hour. The 3 and 5 millimeter water contours were superimposed.

Table 2. Observed wind velocities for Test No. 2.

Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.
15		75	
	3.0		1.5
17		77	
	3.6		4.8
19		79	
	3.6		2.1
21		81	
	1.5		2.7
23		83	
	3.0		0.6
25		85	
	1.5		5.1
27		87	
	2.7		4.2
29		89	
	3.9		2.4
31		91	
Interval average	2.8	Interval average	2.9
46		102	
	5.1		7.2
48		104	
	4.8		7.5
50		106	
	3.3		5.1
52		108	
	2.1		2.7
54		110	
	4.2		3.0
56		112	
	3.9		7.2
58		114	
	2.7		7.2
60		116	
Interval average	3.7	Interval average	5.7

Period average wind velocity = 3.8 km./hr.
Range = 0.6 to 7.5 km./hr.

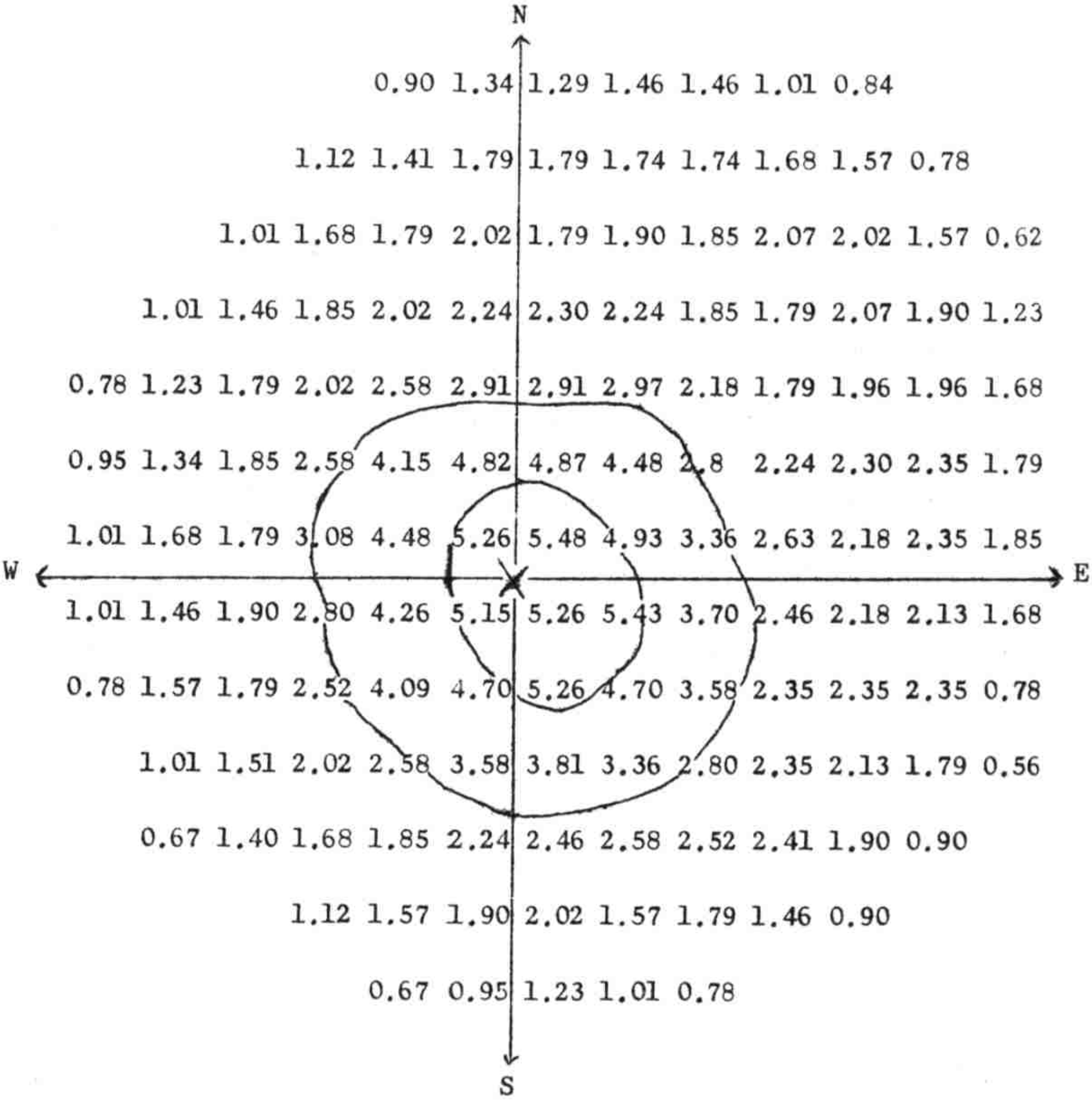

Figure 4. Water distribution pattern - Test No. 3, 7:00 AM to 11:00 AM, September 26, 1962.
Figures shown are depth of application in millimeters per hour.
The 3 and 5 millimeter water contours were superimposed.

Table 3. Observed wind velocities for Test No. 3.

Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.
15		75		135		195	
	0.3		3.0		2.4		2.1
17		77		137		197	
	0.0		4.2		5.1		0.3
19		79		139		199	
	0.3		5.4		3.6		3.9
21		81		141		201	
	0.0		4.5		1.8		7.2
23		83		143		203	
	0.0		6.6		4.2		9.6
25		85		145		205	
	0.0		6.3		0.6		5.4
27		87		147		207	
	0.0		5.4		1.8		6.6
29		89		149		209	
	0.0		4.8		1.5		4.2
31		91		151		211	
Interval average	0.1	Interval average	5.0	Interval average	2.6	Interval average	4.9
46		106		166		226	
	0.9		5.1		0.3		1.8
48		108		168		228	
	0.6		5.4		0.0		1.2
50		110		170		230	
	1.2		5.4		5.7		3.3
52		112		172		232	
	1.2		6.0		2.7		3.0
54		114		174		234	
	1.8		5.1		1.8		3.0
56		116		176		236	
	2.7		0.6		2.1		2.7
58		118		178		238	
	0.6		5.1		1.8		3.0
60		120		180		240	
Interval average	1.3	Interval average	4.7	Interval average	2.1	Interval average	2.6

Period average wind velocity = 2.9 km./hr.
Range = 0.0 to 9.6 km./hr.

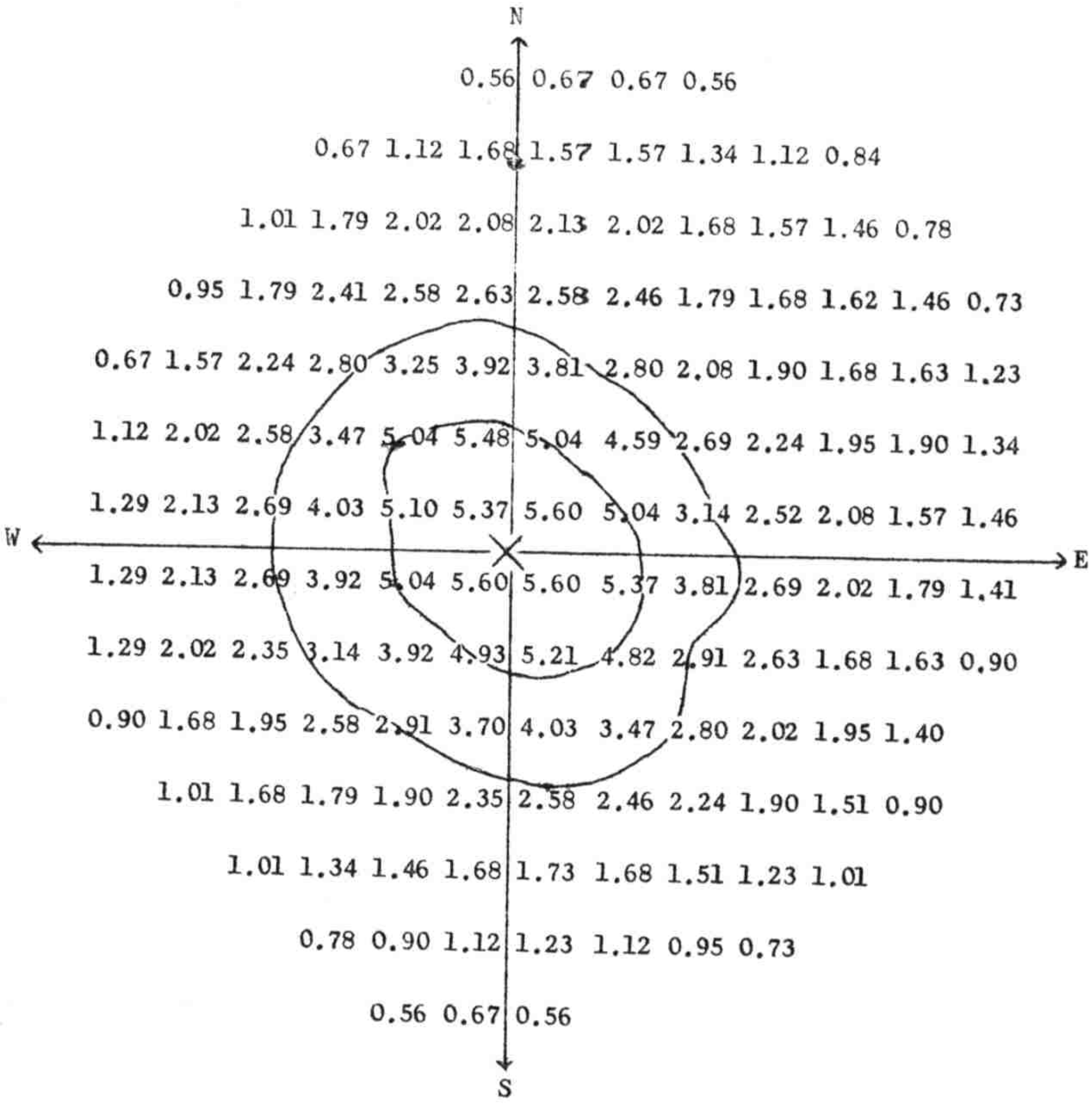

Figure 5. Water distribution pattern - Test No. 4, 6:30 AM to 10:30 AM, October 1, 1962.
Figures shown are depth of application in millimeters per hour. The 3 and 5 millimeter water contours were superimposed.

Table 4. Observed wind velocities for Test No. 4.

Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.
15		75		135		195	
	3.6		1.5		1.2		7.5
17		77		137		197	
	3.6		1.2		2.1		6.6
19		79		139		199	
	3.3		0.6		2.1		6.0
21		81		141		201	
	3.0		1.8		4.5		5.7
23		83		143		203	
	2.4		1.8		3.3		6.3
25		85		145		205	
	1.8		2.7		2.4		8.4
27		87		147		207	
	2.1		3.6		2.1		4.5
29		89		149		209	
	3.9		4.5		1.8		3.3
31		91		151		211	
Interval average	<u>3.0</u>	Interval average	<u>2.2</u>	Interval average	<u>2.4</u>	Interval average	<u>6.0</u>
46		106		166		223	
	4.2		2.4		5.4		6.3
48		108		168		225	
	4.5		2.7		3.9		6.3
50		110		170		227	
	4.2		1.5		4.2		4.5
52		112		172		229	
	4.2		0.3		6.3		7.8
54		114		174		231	
	4.5		0.9		4.8		6.0
56		116		176		233	
	4.5		1.5		6.3		5.1
58		118		178		235	
	3.9		3.0		4.8		5.4
60		120		180		237	
Interval average	<u>4.3</u>	Interval average	<u>1.8</u>	Interval average	<u>5.1</u>	Interval average	<u>5.9</u>

Period average wind velocity = 3.8 km./hr.
Range = 0.3 to 8.4 km./hr.

and the sprinkler is the common center. The area between each two successive wetted circles or contour lines receives an average depth of water equal to the average of the two depths received at the wetted circles.

Tables 1, 2, 3, and 4 show the recorded wind velocities for experimental tests 1, 2, 3, and 4, respectively. The velocities are in kilometers per hour averaged for each 2 minutes. These velocities were averaged to give an average wind velocity for each 14 or 16 minutes interval of wind observation. The average wind speed during the whole test period was calculated by averaging the interval average wind velocities.

The period average wind velocities for tests 1, 2, 3, and 4 were 3.4, 3.8, 2.9, and 3.8 kilometers per hour, respectively. In all these tests the range of wind velocities was between 0 and 10 kilometers per hour.

Experimental tests 5, 6, 7, and 8 were selected to represent the actual water distribution under the dominant high winds which occur in the afternoons. The distribution patterns of these tests are presented in figures 6, 7, 8, and 9 respectively. It is clearly shown that these distribution patterns are typical of the non-uniform water application obtained when sprinklers are operated under high winds. The direct effect of high winds on the water distribution is manifested through the irregular water application contour lines drawn on figures 6 to 9 and representing the 5 and 3 millimeter levels. The contour lines, which are lines of equal wetting, are no more circular under high wind. The sprinkler is no longer the center of water distribution. The highest concentration of water applied was shifted to a north-east position. In general, the spray was transferred to the leeward side because the general direction of wind was south-west.

Tables 5, 6, 7, and 8 show the recorded wind velocities for tests 5, 6, 7, and 8 in kilometers per hour. The period average wind velocities for tests 5, 6, 7, and 8 were 16.6, 22.0, 16.4, and 17.0 kilometers per hour, respectively. The range was from 3 to 37 kilometers per hour.

A comparison of the distribution patterns obtained under low wind (figures 1 to 4) with those obtained under high wind (figures 5 to 8) shows the following:

1. Uniform and regular water distribution was achieved when sprinkling in the mornings under low wind movement.

2. Non-uniform and distorted water distribution was achieved when sprinkling in the afternoons under high wind movement.

3. The wetted area under low wind was larger than that under high wind, while the average depth of water applied to the wetted area under high wind was more than that under low wind. This is attributed to the effect of high wind causing a shift of spray towards the north-east side of the sprinkler. The fine spray carried by the strong wind beyond the wetted

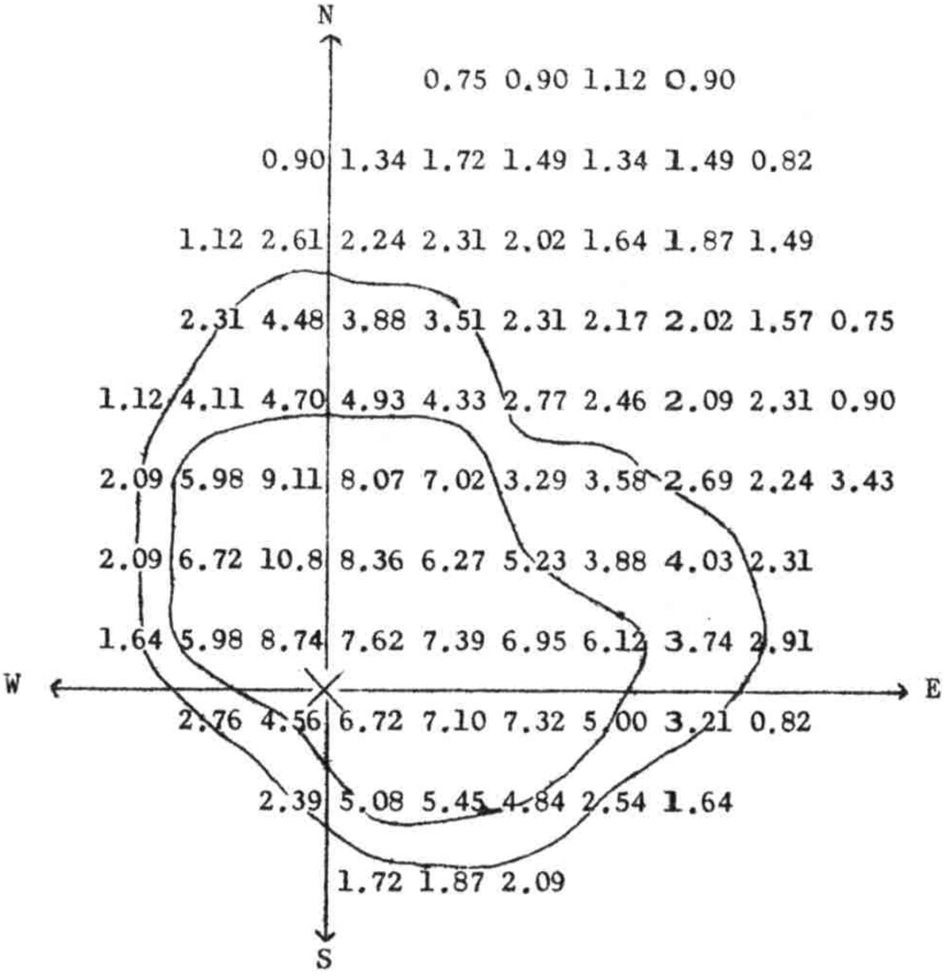

Figure 6. Water distribution pattern - Test No. 5, 2:00 PM to 5:00 PM, September 25, 1962.
Figures shown are depth of application in millimeters per hour. The 3 and 5 millimeter water contours were superimposed.

Table 5. Observed wind velocity for Test No. 5.

Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.
15		75		135	
	16.2		19.8		20.1
17		77		137	
	18.0		22.2		18.3
19		79		139	
	11.7		16.8		21.0
21		81		141	
	14.7		17.7		19.5
23		83		143	
	16.5		21.0		14.1
25		85		145	
	15.3		19.2		14.4
27		87		147	
	13.8		19.5		18.3
29		89		149	
	6.3		17.7		18.3
31		91		151	
Interval average	14.1	Interval average	19.2	Interval average	18.0
46		106		164	
	11.1		21.9		10.8
48		108		166	
	17.7		21.3		13.2
50		110		168	
	19.2		20.7		8.4
52		112		170	
	18.0		18.6		6.6
54		114		172	
	15.9		16.8		10.8
56		116		174	
	21.6		18.0		13.5
58		118		176	
	20.4		15.9		15.6
60		120		178	
Interval average	17.7	Interval average	19.0	Interval average	11.3

Period average wind velocity = 16.6 km./hr.
Range = 6.3 to 22.2 km./hr.

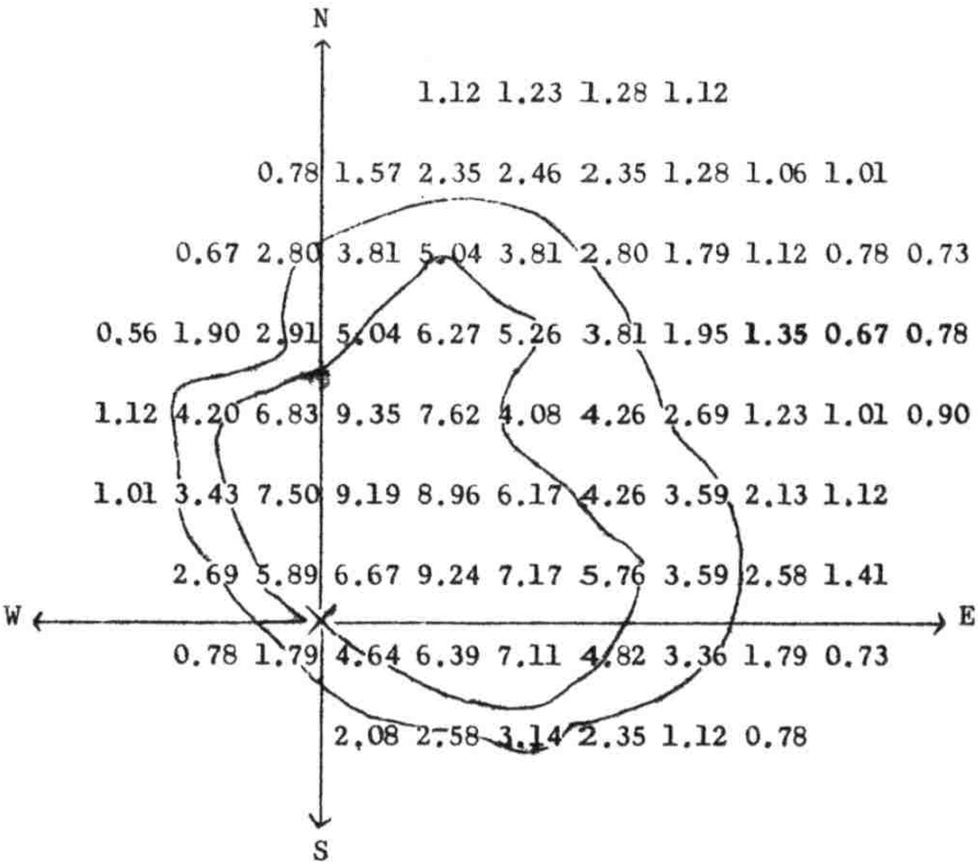

Figure 7. Water distribution pattern - Test No. 6, 1:00 PM to 5:00 PM, September 26, 1962.
Figures shown are depth of application in millimeters per hour.
The 3 and 5 millimeter water contours were superimposed.

Table 6. Observed wind velocity for Test No. 6.

Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.
15		75		135		195	
	18.9		21.3		24.6		24.6
17		77		137		197	
	17.1		27.9		27.9		23.4
19		79		139		199	
	13.8		18.9		27.9		22.5
21		81		141		201	
	19.8		22.2		27.9		22.2
23		83		143		203	
	27.3		31.5		29.1		24.3
25		85		145		205	
	24.9		26.1		27.6		19.8
27		87		147		207	
	18.9		25.8		22.2		19.5
29		89		149		209	
	12.6		21.9		24.3		17.7
31		91		151		211	
Interval average	**12.6**	Interval average	**24.4**	Interval average	**26.4**	Interval average	**21.8**
46		106		166		226	
	11.4		16.5		31.5		19.2
48		108		168		228	
	19.5		11.1		23.7		21.6
50		110		170		230	
	21.0		15.3		36.9		19.4
52		112		172		232	
	15.3		20.4		28.8		21.0
54		114		174		234	
	10.2		22.5		28.2		19.2
56		116		176		236	
	10.5		27.6		28.2		18.0
58		118		178		238	
	18.6		27.9		25.8		21.0
60		120		180		240	
Interval average	**15.2**	Interval average	**20.2**	Interval average	**29.0**	Interval average	**19.9**

Period average wind velocity = 22.0 km./hr.
Range = 10.2 to 36.9 km./hr.

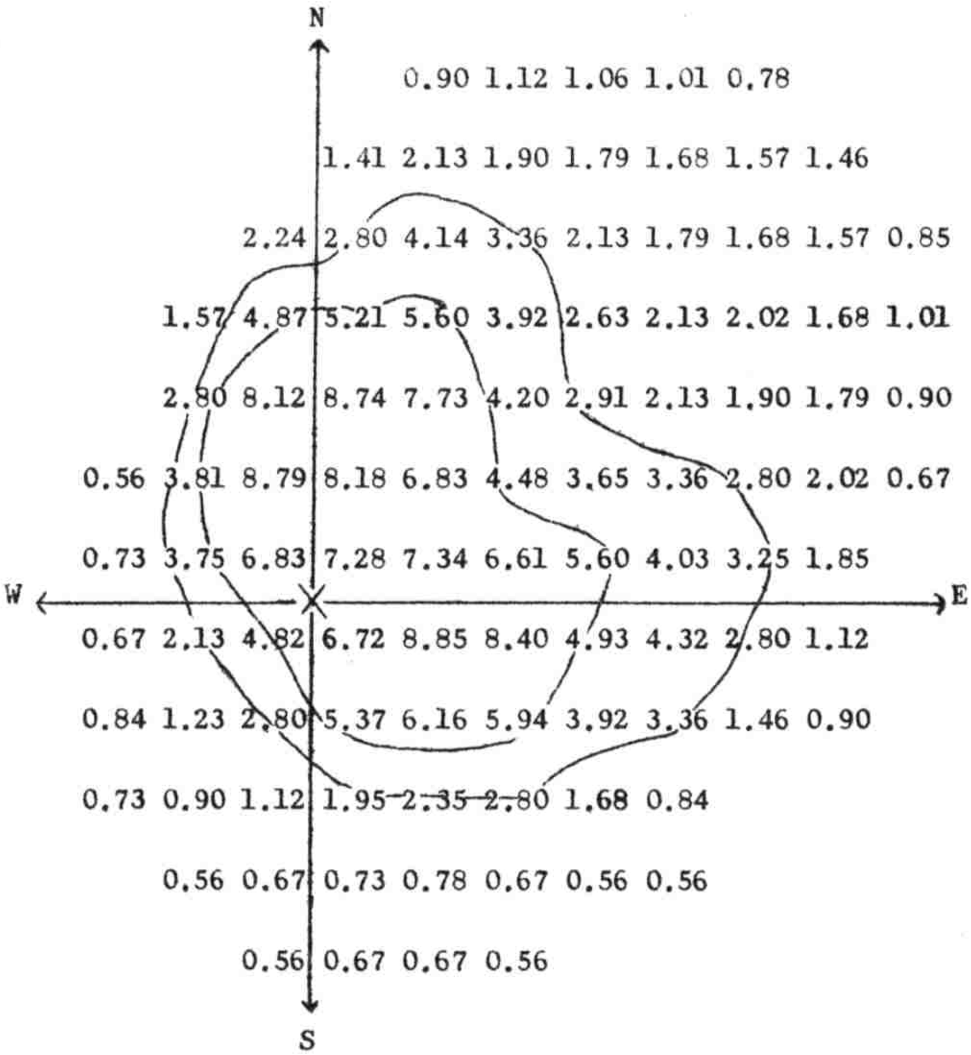

Figure 8. Water distribution pattern - Test No. 7, 1:30 PM to 5:30 PM, September 29, 1962.
Figures shown are depth of application in millimeters per hour. The 3 and 5 millimeter water contours were superimposed.

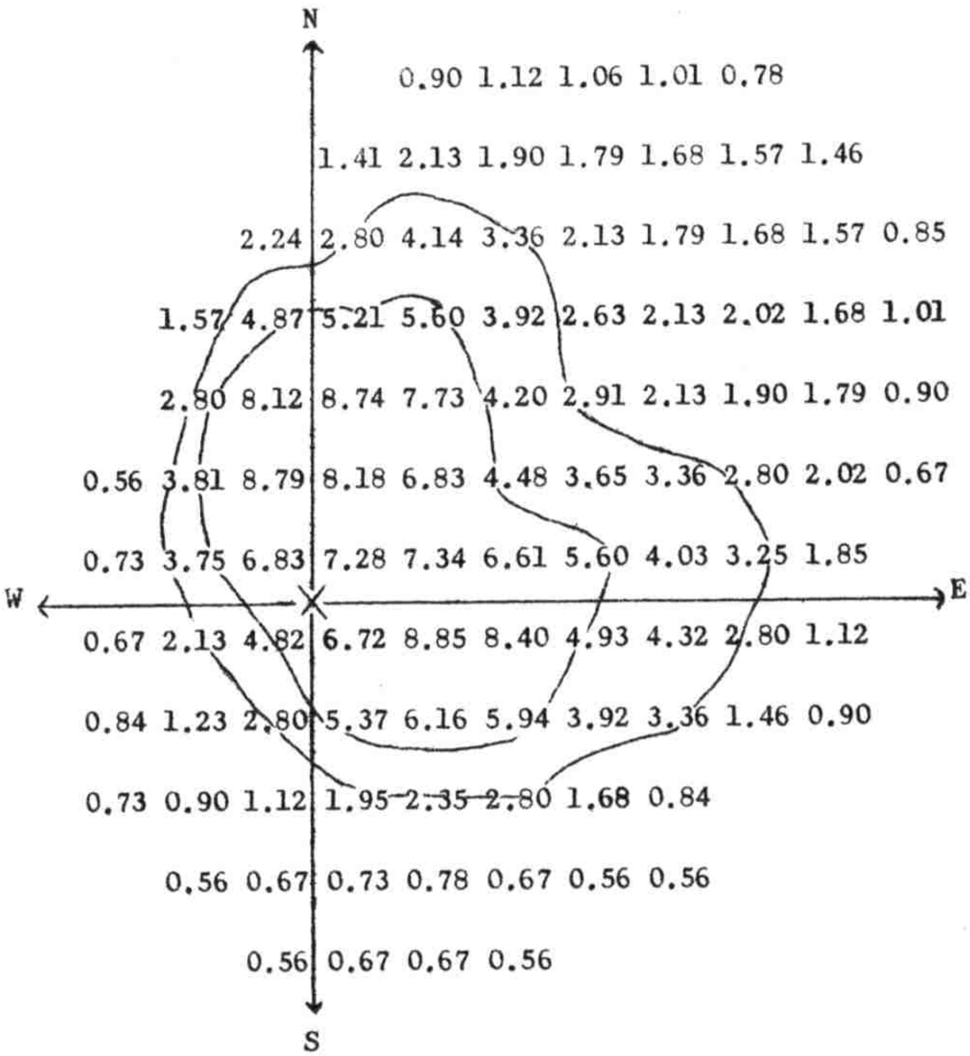

Figure 8. Water distribution pattern - Test No. 7, 1:30 PM to 5:30 PM, September 29, 1962.
Figures shown are depth of application in millimeters per hour.
The 3 and 5 millimeter water contours were superimposed.

Table 7. Observed wind velocities for Test No. 7.

Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.
15		75		135		195	
	17.7		3.9		18.0		17.1
17		77		137		197	
	17.1		3.9		21.3		21.0
19		79		139		199	
	21.0		7.2		19.8		19.5
21		81		141		201	
	21.9		14.7		17.1		15.0
23		83		143		203	
	20.4		18.3		15.6		23.1
25		85		145		205	
	18.6		16.5		22.5		19.2
27		87		147		207	
	18.9		14.1		20.4		19.2
29		89		149		209	
	18.9		8.1		20.4		17.1
31		91		151		211	
Interval average	19.3	Interval average	10.8	Interval average	19.4	Interval average	18.9
46		106		166		223	
	19.2		10.5		13.2		21.9
48		108		168		225	
	16.5		9.6		14.7		21.0
50		110		170		227	
	14.1		9.9		20.1		20.4
52		112		172		229	
	14.7		8.1		19.2		19.5
54		114		174		231	
	15.0		7.2		21.9		22.2
56		116		176		233	
	15.3		5.4		20.4		22.5
58		118		178		235	
	13.8		3.3		18.9		18.9
60		120		180		237	
Interval average	15.5	Interval average	7.7	Interval average	18.3	Interval average	20.9

Period average wind velocity = 16.4 km./hr.
Range = 3.3 to 23.1 km./hr.

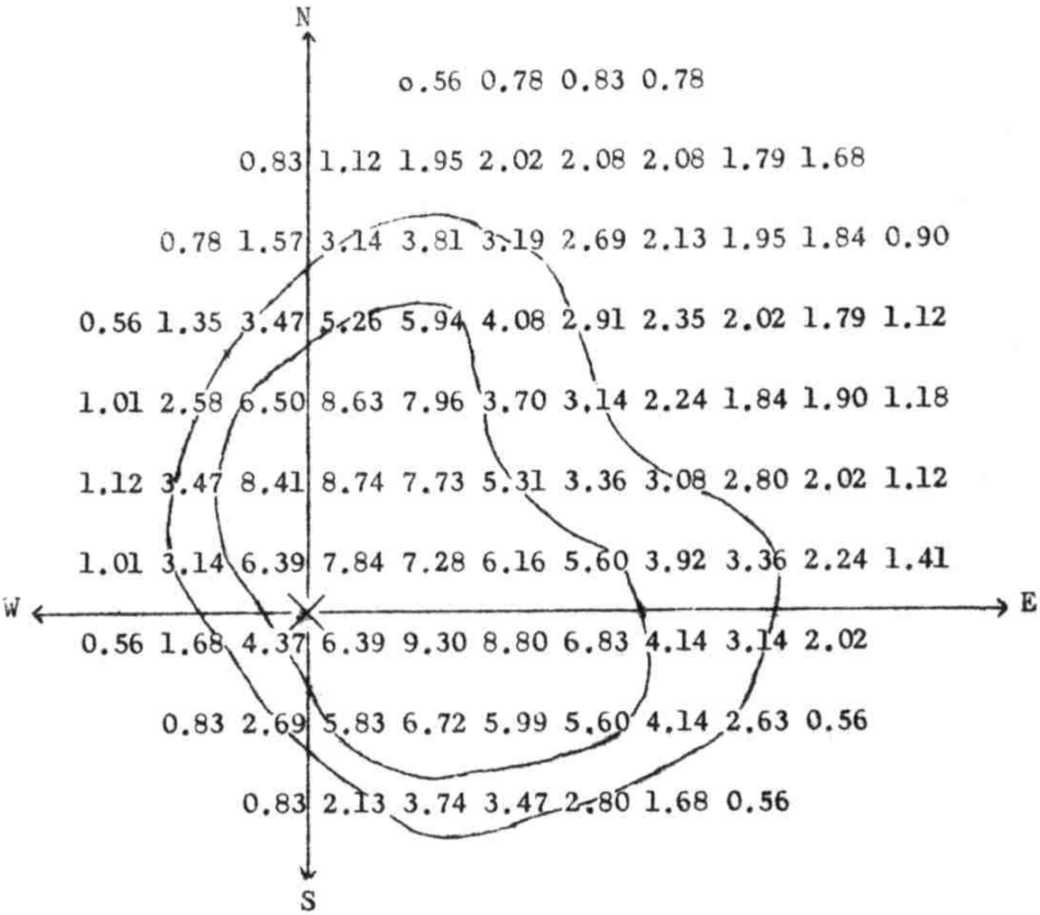

Figure 9. Water distribution pattern - Test No. 8, 1:30 PM to 5:30 PM, September 30, 1962.
Figures shown are depth of application in millimeters per hour. The 3 and 5 millimeter water contours were superimposed.

Table 8. Observed wind velocities for Test No. 8.

Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.	Operating time min.	Average wind velocity km./hr.
15		75		135		195	
	16.8		19.8		20.4		13.5
17		77		137		197	
	15.6		18.6		21.0		12.6
19		79		139		199	
	21.3		20.4		19.2		14.1
21		81		141		201	
	21.3		15.9		16.8		14.7
23		83		143		203	
	15.3		16.8		22.5		12.0
25		85		145		205	
	11.5		14.7		23.4		10.8
27		87		147		207	
	10.6		22.8		21.6		12.6
29		89		149		209	
	15.0		18.3		21.6		12.3
31		91		151		211	
Interval average	15.9	Interval average	18.4	Interval average	20.8	Interval average	12.8
46		106		166		224	
	18.3		17.1		19.8		11.1
48		108		168		226	
	14.7		22.5		22.5		10.5
50		110		170		228	
	20.4		21.0		19.8		10.5
52		112		172		230	
	19.2		19.2		16.2		11.4
54		114		174		232	
	19.8		21.0		16.2		11.4
56		116		176		234	
	20.4		18.3		18.0		10.8
58		118		178		236	
	17.7		18.6		18.6		10.2
60		120		180		238	
Interval average	18.6	Interval average	19.7	Interval average	18.7	Interval average	10.8

Period average wind velocity = 17.0 km./hr.
Range = 10.2 to 23.4 km./hr.

area, reached the ground in non significant amounts. So less area was irrigated under high wind but with an average depth higher than that under low wind. This will be more fully discussed under water application efficiency.

Generalized Distribution Patterns

In order to analyze the distortion caused by wind variations on the sprinkler performance, it was necessary to have an ideal distribution pattern under theoretically no wind conditions. This is practically considered similar to the average low wind condition. Then by keeping this as a check, the effect of high wind on the distribution pattern could be evaluated. On this basis, the first group of 4 tests - Tests No.s 1, 2, 3, and 4 - which were carried out under low wind were synthesized to produce a standard water distribution pattern. This pattern is shown in figure 10 and can be considered as a typical distribution under theoretically no wind conditions but actually low wind conditions. Each figure represents the depth of water in millimeters per hour synthesized by averaging the correspondent depths obtained from the 4 tests. Resultant water application contour lines were drawn. The average wind velocity for this new pattern was calculated by averaging the period average velocities for the 4 tests. This was equal to 3.5 kilometers per hour.

The same was done for the second group of 4 tests -

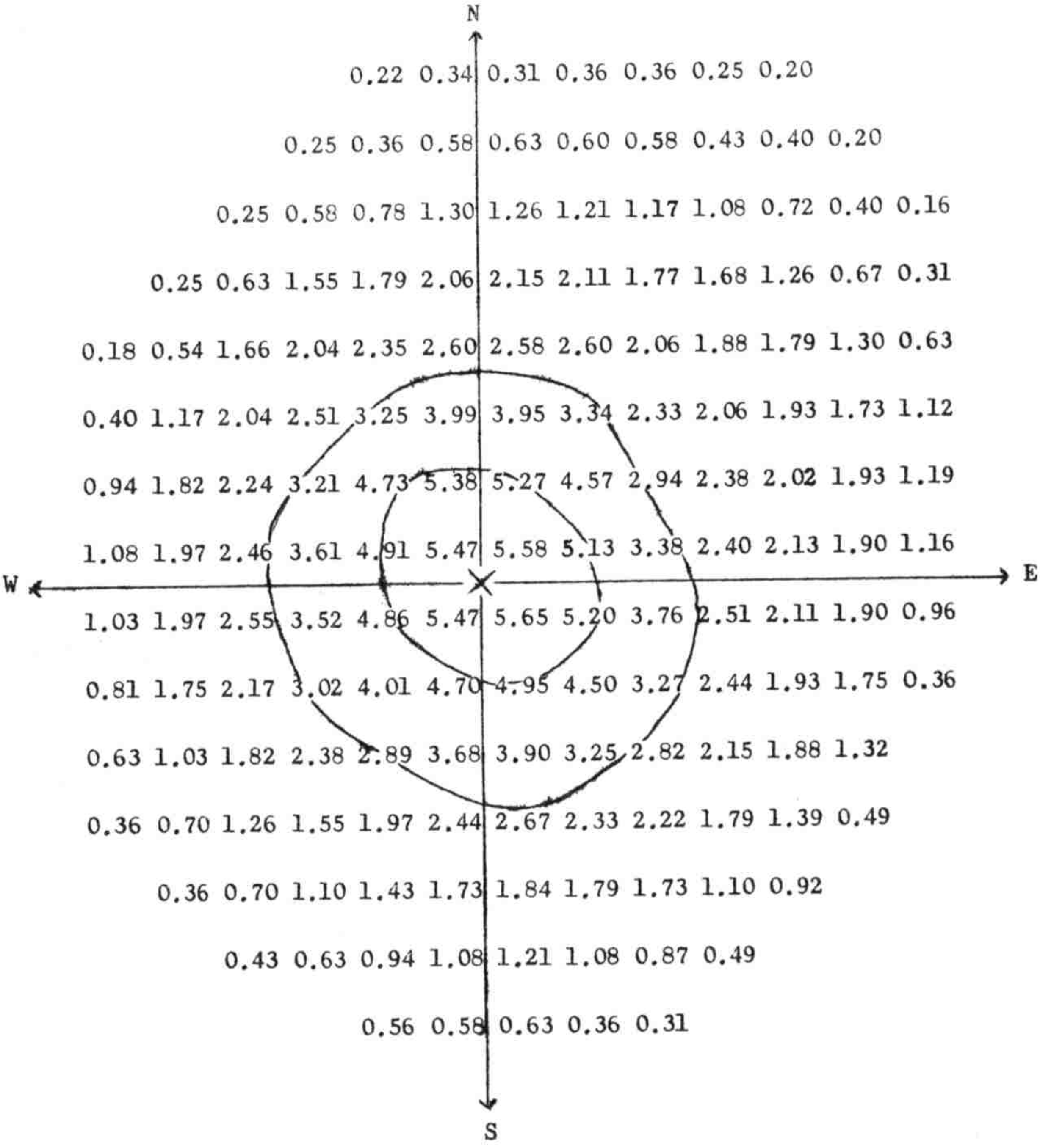

Figure 10. Water distribution pattern - Average of the 4 low wind tests, 1, 2, 3, and 4.
Figures shown are depth of application in millimeters per hour.
The 3 and 5 millimeter water contours were superimposed.

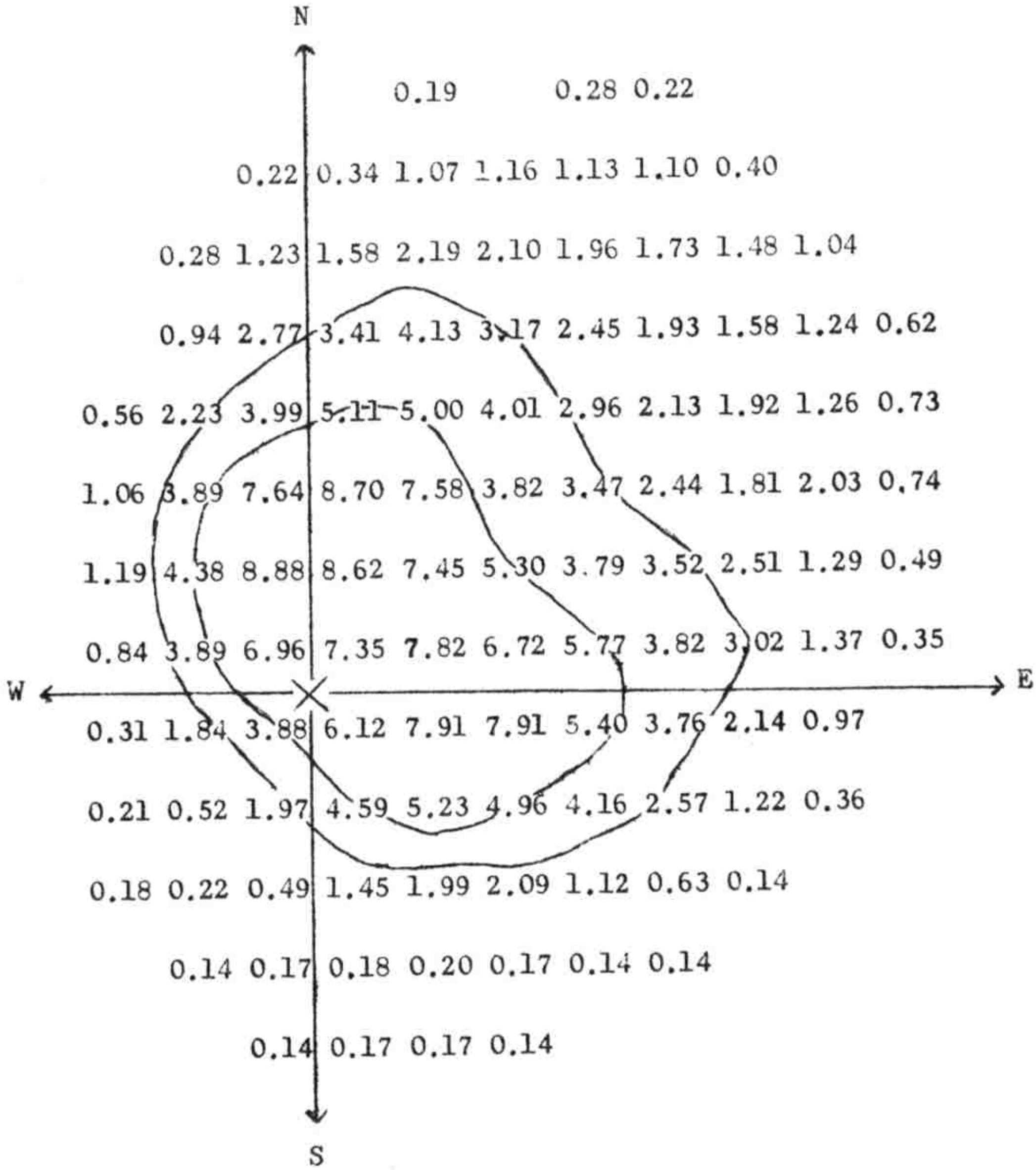

Figure 11. Water distribution pattern - Average of the 4 high wind tests, 5, 6, 7, and 8.
Figures shown are depth of application in millimeters per hour. The 3 and 5 millimeter water contours were superimposed.

Tests No.s 5, 6, 7, and 8 - and a water distribution pattern was synthesized to represent an average distribution under high wind. This pattern with its irregular resultant water application contour lines is shown in figure 11. The average wind velocity for this pattern was equal to 18.0 kilometers per hour.

To illustrate more fully the water distribution under high wind and low wind conditions, the distribution curves were drawn from data obtained from figures 10 and 11, using values lying adjacent to the W-E axis. Figure 12 shows the distribution curve under low wind. It may be observed that the distribution of water was regularly decreasing along both sides of the sprinkler and the highest depth was centered around the sprinkler. A similar curve was obtained from the values lying adjacent to NS axis, but is not shown. Figure 12 shows the distribution curve under high wind. It is clearly shown that the distribution was shifted to the east side of the sprinkler but not in a regular manner. The highest concentration was about 3 meters to the east and 3 meters to the north sides of the sprinkler as shown in figure 11.

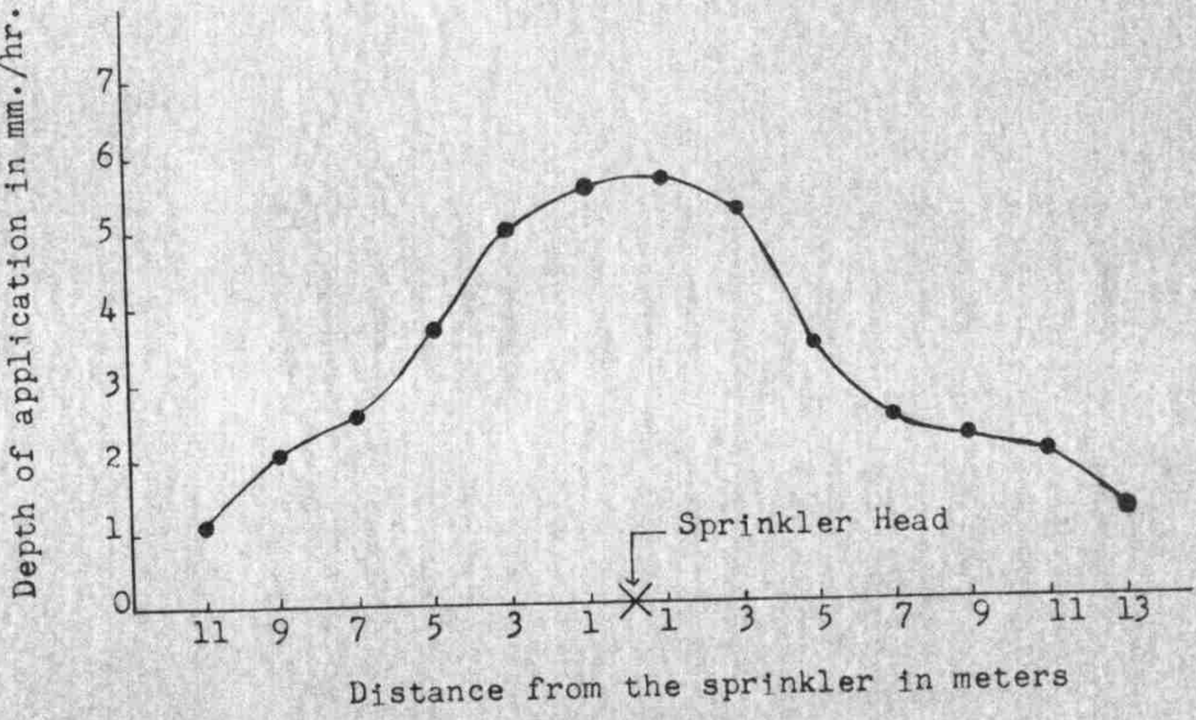

Figure 12. Distribution curve for low wind. Data obtained from figure 10, using values lying adjacent to W-E axis.

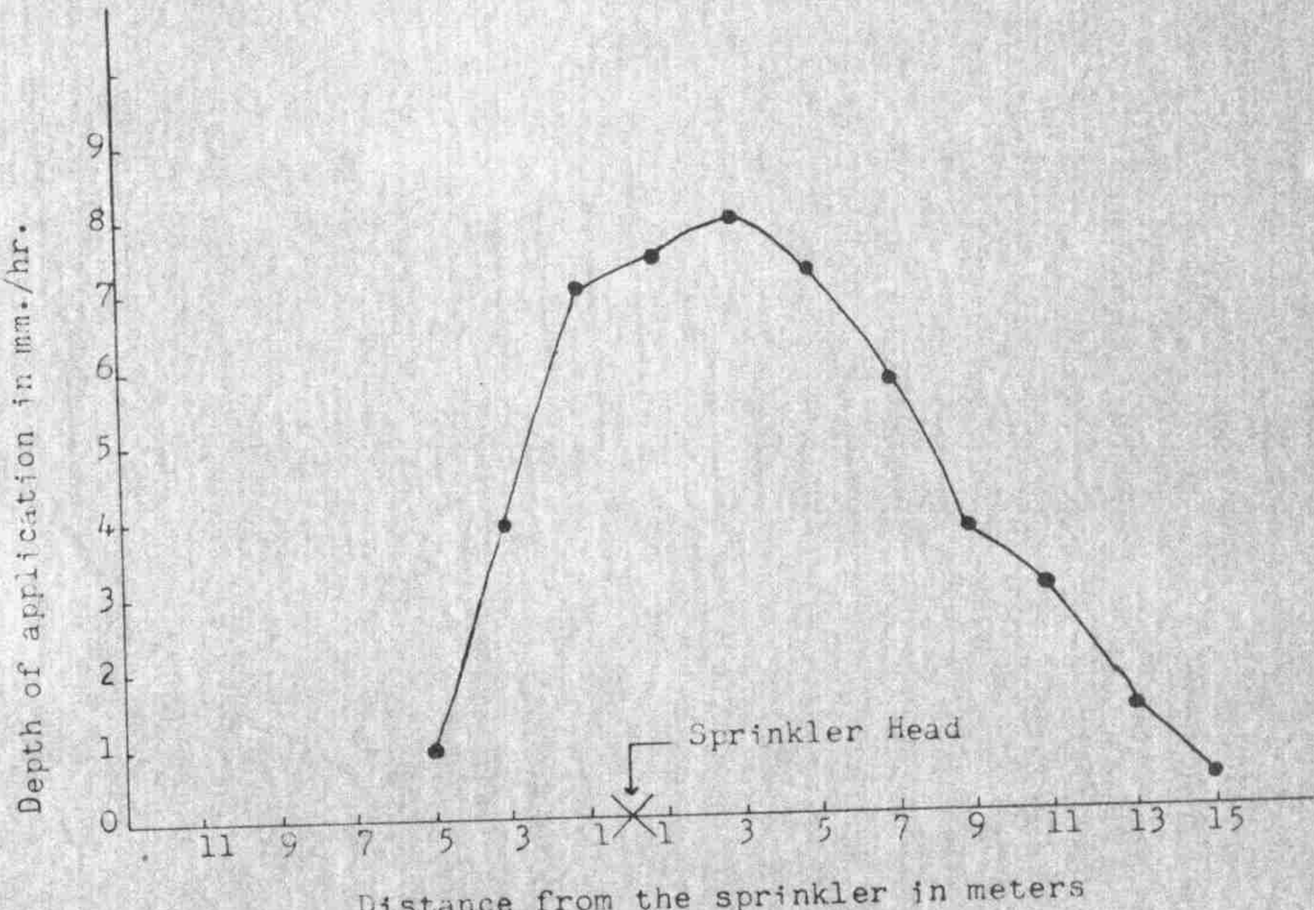

Figure 13. Distribution curve for high wind. Data obtained from figure 11, using values lying adjacent to W-E axis.

Uniformity Coefficient

The effect of varying wind conditions on the distribution pattern of an existing sprinkler system was evaluated through the determination of the resulting variations in the uniformity coefficient. First, a suitable layout for low wind conditions was determined. Suitability was based on the attainment of a high uniformity coefficient. Then the effect of high wind conditions on this uniformity coefficient was evaluated. Similarly, a suitable layout for high wind conditions was determined on the same basis, and its performance under low wind conditions was evaluated.

1. Selection of a suitable layout for low wind conditions.

The data used in this analysis are those values obtained in the standard distribution pattern synthesized for low wind(figure 10). The distribution from the sprinkler, as stated before, starts with a high concentration or depth of application around the sprinkler and decreases uniformly with distance from the sprinkler towards the margins of the wetted area. Therefore, it was necessary to overlap the wetted areas so that a uniform depth of water would be applied all over the irrigated area. Otherwise parts of the land would be overirrigated and parts underirrigated. By overlapping is meant a selection of spacings between sprinklers and laterals so that enough sprinklers would apply water to each unit area to give a uniform depth over all the wetted area. To test the uniformity of water application from a certain spacing of sprinklers and laterals, the uniformity coefficient was calculated. The layout - spacing between sprinklers and between laterals - that gives the highest uniformity coefficient is considered to be the best layout from a theoretical point of view. However there are some other limiting factors for using a certain layout besides the uniformity coefficient. The most important of these are:

A. The infiltration capacity of the soil in question. If the average application rate in depth per hour exceeds the soil infiltration capacity, runoff losses will be unavoidable. Therefore it is necessary that the depth applied be equal to or less than the infiltration capacity, even though the uniformity coefficient would not be the highest.

B. Equipment availability and labor facilities. The farmer cannot set his sprinklers and laterals close enough to get the highest uniformity coefficient if he does not have enough equipment. Or he cannot provide the required labor in order to irrigate his land in the proper time schedule.

C. Economical justification. This actually should be the basic consideration in selecting the layout and should compare the advantages of a higher uniformity coefficient with the extra expenses required for its execution.

In order to find out the best layout between sprinklers and laterals for the sprinkler distribution under low wind conditions different spacings were tested by the uniformity coefficient. The range of spacings to be tested was obtained by overlapping different distribution curves similar to that shown in figure 12. Assuming the sprinklers would be placed at a given spacing and each would give the same distribution curve as that shown, accumulated application rates were obtained by adding the depths contributed from each sprinkler. Spacings resulting in an approximate uniform or straight line distribution curve were considered worthy of further testing.

The detailed procedure for calculating the uniformity coefficient is shown only for the 12 x 12 meter spacings. A plan showing the proposed layout for the 12 x 12 meter spacing for low wind is presented in figure 14. Each sprinkler was assumed to give a water distribution exactly the same as the one synthesized in figure 10. The area bounded by the 4 sprinklers Nos. 1, 2, 3, and 4 was considered to be the test area. Any amount of water that would fall in the test area from any of the sprinklers was recorded at the appropriate position. This was done by superimposing the sprinkler distribution of figure 10 at each of the proposed positions in figure 14, then the data in figure 10 that would be contributed from each sprinkler were inserted in the test area at the appropriate positions. The values contributed from each sprinkler were placed in the order of sprinkler numbering. The detailed data obtained are shown in figure 15. The first value in each position was contributed from sprinkler number 1, the second from sprinkler No. 2 and so on. The 9 values were contributed from 9 sprinklers. It may be observed that most of the depths are applied from the 4 sprinklers surrounding the test plot. All the collected depths or values applied at each position were added. The figures shown are depth of application in millimeters per hour, that would be obtained under low wind condition, and by using the 12 x 12 meter spacing.

The uniformity coefficient was calculated by using Christiansen formula(8):

$$CU = 100 \left[1 - \frac{\Sigma Y}{mn}\right]$$

in which CU = coefficient of uniformity

Y = difference between individual observations* and the mean of observations.

ΣY = Sum of all of the Y differences for the test area.

mn = total of all observations.

m = mean of observations.

n = number of observations.

Applying this formula to the data in figure 15, table 9 was prepared which shows a uniformity coefficient of 93.90% for the 12 x 12 meter spacing under low wind. The same procedure was followed for determining the uniformity coefficients for all other spacings.

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* Observation refers to collected depth at each position.

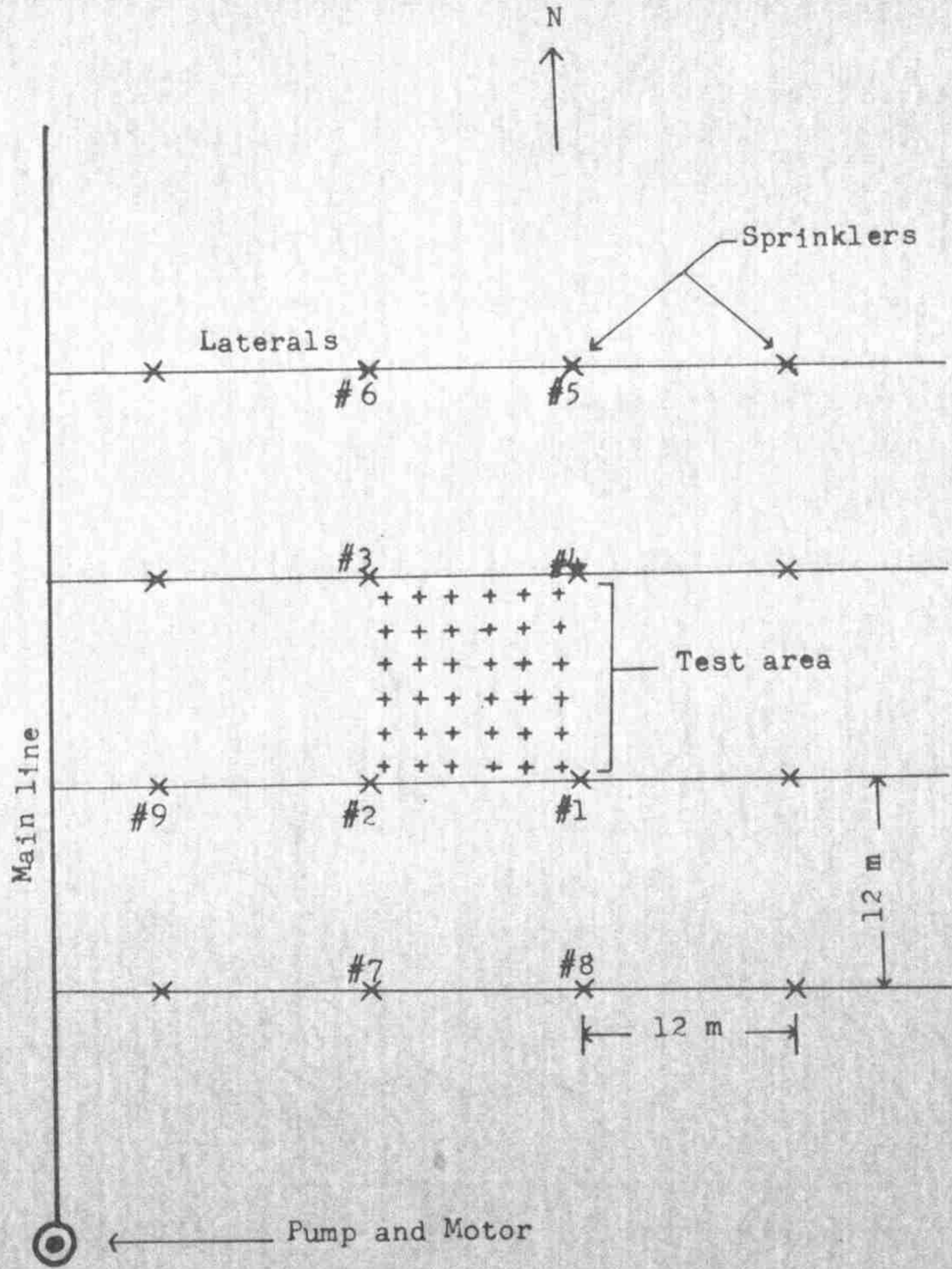

Figure 14. Plan for the proposed 12 x 12 meter layout.

3 X | | | | | 4 X

- (1) 0.63(6) 1.26(2) - (7) 5.65(3) - (8) 1.03(4) 0.16(9) - (5) 8.73	- 0.36 1.21 - 5.20 - 1.97 - - 8.74	0.25 0.31 1.17 - 3.76 - 2.55 - - 8.04	0.58 - 1.08 - 2.51 - 3.52 - - 7.69	0.78 - 0.72 - 2.11 - 4.86 - 0.56 9.03	1.30 - 0.40 - 1.90 - 5.47 - 0.58 9.65
- - 2.15 - 4.95 - 0.81 0.31 - 8.22	0.25 - 2.11 - 4.50 - 1.75 - - 8.61	0.63 - 1.77 - 3.27 - 2.17 - - 7.84	1.55 - 1.68 - 2.44 - 3.02 - - 8.69	1.79 - 1.26 - 1.93 - 4.01 - - 8.99	2.06 - 0.67 - 1.75 - 4.70 - - 9.18
0.18 - 2.58 - 3.90 - 0.63 0.63 - 7.92	0.54 - 2.60 - 3.25 - 1.03 - - 7.42	1.66 - 2.06 - 2.82 - 1.82 - - 8.36	2.04 - 1.88 - 2.15 - 2.38 - - 8.45	2.35 - 1.79 - 1.88 - 2.89 - - 8.91	2.60 - 1.30 - 1.32 - 3.68 - - 8.90
0.40 - 3.95 - 2.67 - 0.36 1.12 - 8.50	1.17 - 3.34 - 2.33 - 0.70 - - 7.54	2.04 - 2.33 - 2.22 - 1.26 - - 7.85	2.51 - 2.06 - 1.79 - 1.55 - - 7.91	3.25 - 1.93 - 1.39 - 1.97 - - 8.54	3.99 - 1.73 - 0.49 - 2.44 - - 8.65
0.94 - 5.27 0.31 1.84 - - 1.19 - 9.55	1.82 - 4.57 0.36 1.79 - 0.36 - - 8.90	2.24 - 2.94 0.36 1.73 - 0.70 - - 7.97	3.21 - 2.38 0.25 1.10 - 1.10 - - 8.04	4.73 - 2.02 0.20 0.92 0.22 1.43 - - 9.52	5.38 - 1.93 - - 0.34 1.73 - - 9.38
1.08 - 5.58 0.63 1.21 - - 1.16 - 9.66	1.97 - 5.13 0.60 1.08 - - - - 8.78	2.46 - 3.38 0.58 0.87 - 0.43 - - 7.72	3.61 - 2.40 0.43 0.49 0.25 0.63 - - 7.81	4.91 - 2.13 0.40 - 0.36 0.94 - - 8.74	5.47 - 1.90 0.20 - 0.58 1.08 - - 9.23

X 2 | | | | | X 1

Figure 15. Chart showing depth of water contributed by sprinklers in order of their numbers as shown by figure 14. The values are obtained from figure 10. Spacing 12 x 12 meters - low wind.

Table 9. Uniformity coefficient calculation for the 12 x 12 meter layout.

Observation	Absolute Difference Y
8.73	0.18
8.22	0.33
7.92	0.63
8.50	0.05
9.55	1.00
9.66	1.11
8.74	0.19
8.61	0.06
7.42	1.13
7.54	1.01
8.90	0.35
8.78	0.23
8.04	0.51
7.84	0.71
8.36	0.19
7.85	0.70
7.97	0.58
7.72	0.83
7.69	0.86
8.69	0.14
8.45	0.10
7.91	0.64
8.04	0.51
7.81	0.74
9.03	0.48
8.99	0.44
8.91	0.36
8.54	0.01
9.52	0.97
8.74	0.19
9.65	1.10
9.18	0.63
8.90	0.35
8.65	0.10
9.38	0.83
9.23	0.68
Total=307.66	18.74

m=8.55

$m = 8.55$ mm/hr., $n = 36$

$$\text{Uniformity Coefficient} = 100\left[1 - \frac{Y}{mn}\right]$$

$$= 100\left[1 - \frac{18.74}{307.66}\right]$$

$$= 100 - 6.10$$

$$= 93.90\%$$

Table 10 shows the different square and rectangular spacings tested and their corresponding uniformity coefficients. The range of spacings was from 8 to 16 meters. The nature of the field data obtained did not allow an exact testing of triangular spacings. To be able to carry out such a test the field location of catching cans should have been altered. This alteration would not have allowed a testing of rectangular and square spacings. Field tests covering both arrangements would have taken more field time than was available, and since triangular spacings are not commonly utilized, it was deemed advisable to follow the presented data.

Table 10. Calculated uniformity coefficients for different spacings under low wind condition.

Spacings tested meters		Uniformity coefficient %
between sprinklers	between laterals	
14	16	85.5
14	14	91.3
12	14	92.6
12	12	93.9
10	12	92.8
8	10	91.6

The results in table 10 show that the uniformity coefficient increases as the spacing between sprinklers and/or laterals decreases but up to a certain point where, thereafter the relation is reversed. The spacing between sprinklers and laterals that produced the highest uniformity coefficient was selected as the optimum theoretical design or layout. This spacing was 12 x 12 meter square resulting in a uniformity coefficient of 93.90%.

Assuming the average low wind conditions would prevail during the sprinkler operation period, the 12 x 12 meter layout would be considered the most suitable, as it would give the highest uniformity distribution coefficient. However, if the winds increase in strength a reduced uniformity coefficient will result, and a new design should be formulated to meet the effect of high wind. The effect of high wind and the new design to overcome such effect are the two items studied in the following sections.

2. Effect of high wind on the suitable layout designed for low wind conditions.

Applying the same technique utilized for determining the uniformity coefficient under low wind conditions but using the distribution data synthesized for high wind (figure 11), the data in figure 16 were obtained. The uniformity coefficient, determined similarly, for the 12 x 12 meter layout under high wind amounted to 80.39%. This 80.39% uniformity coefficient obtained under high wind is less than the one obtained under low wind by 13.51%.

Another demonstration of the effect of high wind on water distribution is shown by the variability of depths of water received at the test areas. In the case of low wind,

X						X
	9.71	10.10	10.01	7.67	7.61	8.73
	9.60	9.98	8.13	6.82	5.96	7.54
	8.82	7.72	6.10	4.82	5.21	6.54
	10.91	8.52	<u>3.99</u>	4.67	6.61	9.62
	10.08	8.30	5.44	5.26	8.12	<u>11.53</u>
X	9.06	9.24	7.88	7.74	8.81	10.60 X

Total of all observations, mn = 287.45 mm/hr.

Number of observations, n = 36

Mean of observations, m 7.98 mm/hr.

Sum of all deviations from mean, Y = 56.33 mm/hr.

$$CU = 100\left[1 - \frac{56.33}{287.45}\right] = 100 - 19.61$$

$$= \underline{80.39\%}$$

Figure 16. Determination of uniformity coefficient from collected depths of application in millimeters per hour. Spacing 12 x 12 meter - high wind.

the highest depth is equal to 9.66 mm/hr., and the lowest 7.42 mm/hr., with a difference of 2.24 mm/hr. While in the case of high wind, the highest depth is equal to 11.53 mm/hr., and the lowest 3.99 mm/hr., with a difference of 7.54 mm/hr. This inadequacy of water distribution under high wind will result in parts of the irrigated area being underirrigated and parts overirrigated.

A comparison of the two means or averages of water application at the two test areas, under low and high wind, shows that the mean application under low wind is equal to 8.55 mm/hr. while that under high wind is 7.98 mm/hr. The difference is equal to 0.57 mm/hr. This difference is due to more evaporation and drift losses occuring under high wind. A more detailed explanation and evaluation of this effect is presented under water application efficiency.

3. Selection of a suitable layout for high wind conditions.

The same logic and order of deductions used in selecting a suitable layout for low wind conditions were used here. However, closer spacings were tested in order to overcome the distorting effect of high winds. The data used were the values obtained in figure 11. Figure 17 shows the plan of the layout of 8 x 10 meters, and figure 18 shows the details of the determination of the uniformity coefficient for this layout. The same procedure was followed for all other spacings.

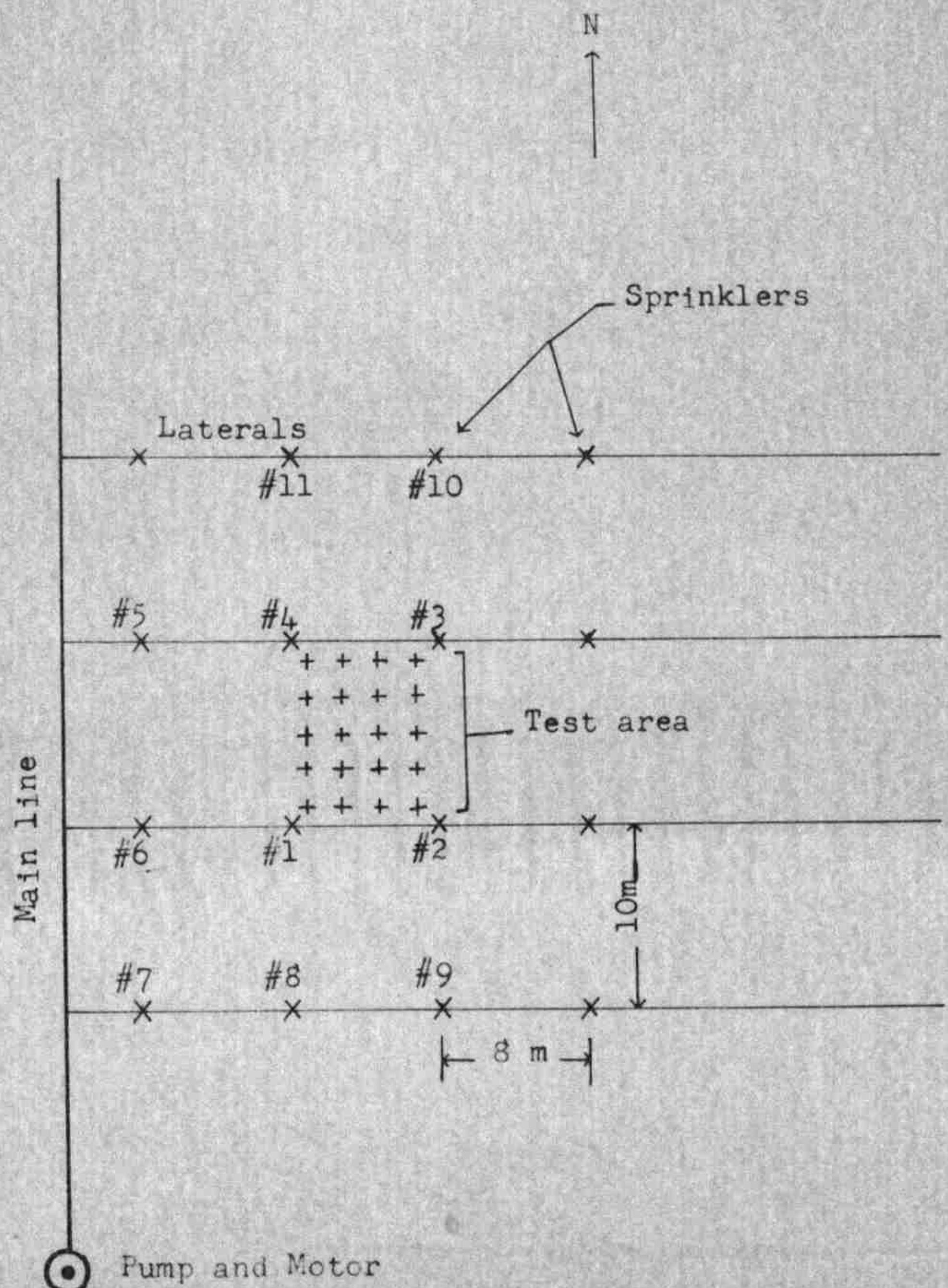

Figure 17. Plan for the proposed 8 x 10 meter layout.

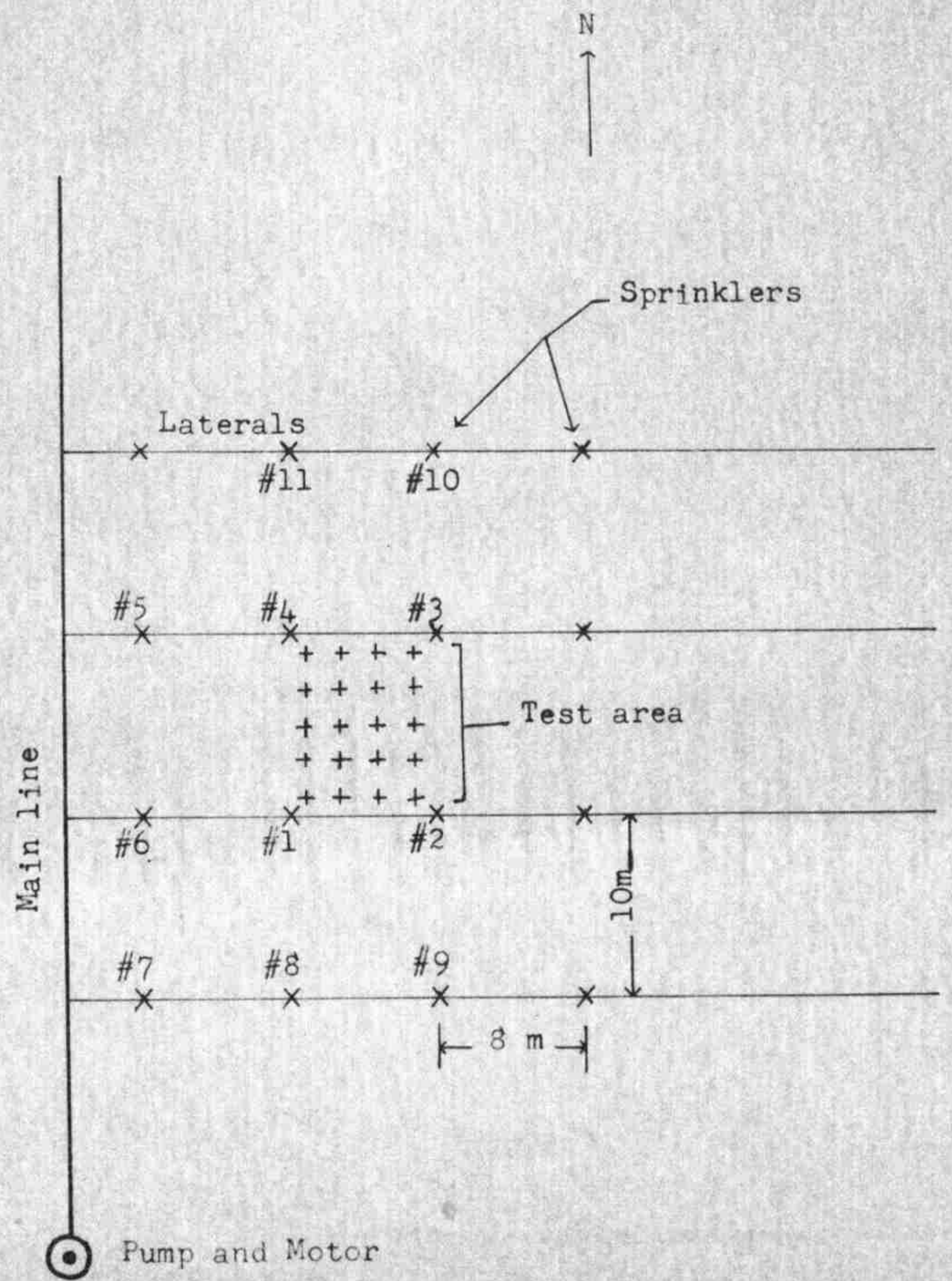

Figure 17. Plan for the proposed 8 x 10 meter layout.

X			X
15.22	16.07	16.07	15.12
14.40	14.14	13.34	13.81
13.44	12.95	12.05	13.74
13.99	12.82	12.44	14.82
14.69	15.52	15.54	16.41
X			X

Total of all observations, mn = 286.45 mm/hr.

Number of observations, n = 20

Mean of observations, m = 14.32 mm/hr.

Sum of all deviations from the mean, Y = 21.19 mm/hr.

$$CU = 100 \left[1 - \frac{21.19}{286.45}\right] = 100 - 7.40$$

$= \underline{92.60\%}$

Figure 18. Determination of uniformity coefficient from collected depths of application in millimeters per hour. Spacing 8 x 10 meter - high wind.

Table 11 shows the different square and rectangular arrangements tested and their corresponding uniformity coefficients. The results show that the layout having 8 meters between sprinklers and 10 meters between laterals gave the highest uniformity coefficient. This layout is considered to be the suitable design in order to overcome the effect of high wind and produce a high uniformity coefficient.

Table 11. Calculated uniformity coefficients for different spacings under high wind conditions.

Spacings tested meters		Uniformity coefficient
between sprinklers	between laterals	
10	14	75.00
12	12	80.39
10	12	84.57
10	10	88.70
8	10	92.60
8	8	91.80

4. Effect of low winds on the suitable layout designed for high wind conditions.

The previous determinations of the uniformity coefficients for low wind spacings, presented in table 10, showed that the 8 x 10 meter layout gave 91.60% uniformity coefficient. The detailed determination of this is shown in figure 19.

The 8 x 10 meter layout gave 92.60% uniformity coefficient under high wind. So, as far as uniformity coeffi-

X 15.99	16.66	15.26	13.29 X
15.71	15.57	13.55	12.20
16.03	14.89	12.99	12.47
15.88	15.13	13.99	13.00
15.86 X	15.72	14.72	13.08 X

Total of all observations, mn = 291.99 mm/hr.

Number of observations, n = 20

Mean of observations, m = 14.60 mm/hr.

Sum of all deviations from the mean, Y = 24.60 mm/hr.

$$CU = 100 \left[1 - \frac{24.60}{291.99}\right] = 100 - 8.40$$

91.60%

Figure 19. Determination of uniformity coefficient from collected depths of application in millimeters per hour. Spacing 8 x 10 meters - low wind.

cients are concerned, the 8 x 10 meter layout works good under both conditions - low and high winds - occuring in Bekaa. The main limitations to the use of this close spacing are the extra labor and equipment required to cover a certain area.

Water Application Efficiency

The water application efficiency of a sprinkler system has been defined as the ratio between the amount of water stored in the root zone, and the amount of water delivered from the sprinkler nozzles. In percentage form(28):

$$Ea = \left(\frac{Ws}{Wf} \right) \times 100$$

where, Ea is the water application efficiency, Ws is the amount of water stored in the root zone, and Wf is the amount of water delivered from the sprinkler nozzles.

The sprinkler discharge, or the volume of water delivered from the sprinkler nozzles was measured during the experimental test, as explained under materials and methods. All the volumetric measurements of the sprinkler discharge gave a constant value due to the fact that all the factors affecting the discharge from the nozzles were kept constant. The sprinkler type, the nozzle size, and the operating pressure were kept the same during the whole experimental period. Wind has no effect on the amount of water that comes out from the sprinkler nozzles, but is effective after the water droplets leave the nozzles. The discharge from the sprinkler nozzles under the 40 pounds pressure was equal to 2080 liters per hour.

The depth of water received at the catch recording cans was assumed equal to the amount of water stored in the root zone. This assumption was based on two considerations. First the water that falls on the ground surface was considered to infiltrate into the soil without runoff because the infiltration capacity of the soil was higher than the application rate for all the arrangements tested. Second, the water infiltrating into the soil was considered to stay in the root zone without deep percolation provided that timing of the irrigation is proper. Also evaporation from cans and evaporation from soil were considered to be the same.

As reported before, the catch recording cans were placed 2 meters apart. Therefore the depth of water received at each can represents the average depth received by an area of 4 square meters. A general look on the water distribution patterns under low and high wind (figures 10 and 11) shows that the wetted area under low wind is more than that under high wind. This is more confirmed by counting the number of catching cans under each condition in figures 10 and 11.

The number of cans catching water under low wind counted from figure 10 is equal to 164 and the wetted area 656 square meters. Under high wind the catching cans are 113 and wetted area is 452 square meters. The difference in wetted area is attributed to the effect of high wind. The South-West high winds shifted the water distribution and concentrated it in the North-East side.

The total volume of water received by the wetted area under each condition was calculated by multiplying the depth received at each can by the area represented by that depth, and adding all the values. The following results were obtained:

Total volume of water received by the wetted area under low wind = 1300 liters per hour.

Total volume of water received by the wetted area under high wind = 1,146 liters per hour.

Water application efficiency was calculated for the two conditions as follows:

Under low wind, $Ea_L = \frac{1,300}{2,080} \times 100 = \underline{62.50\%}$

Under high wind, $Ea_H = \frac{1,146}{2,080} \times 100 = \underline{55.10\%}$

Although actual field measurements were taken, these efficiencies seem to be less than what is claimed by sprinkler manufacturers, and what is reported by some workers. Subsequent or repeated investigations without neglecting any received amounts in the catching cans are needed to confirm these results.

The loss of water from the spray from the time it leaves the sprinkler nozzle until it is stored in the root zone, under low wind, is due mainly to evaporation losses from the droplets while they are in the air and from the soil surface. The drift losses caused by wind, here, might be considered minor. The total loss of the spray under low wind is equal to 37.5 percent of the total water applied.

In case of the distribution under high wind, the losses are attributed to two factors(1):

First is the evaporation losses which are the same as those

under low wind except that more evaporation occurs to the droplets while they are in the air due to the higher wind removing the saturated air faster from around the water drops and to breaking the large drops into smaller ones causing more surface to be subjected to evaporation.
Second is the drift losses. These are very small sized droplets carried away by the wind in a mist like form. These, either remain in suspension or reach the ground beyond the wetted area and are of no significance.

The total loss under high wind is increased to 44.91 percent of the total water applied. The increase over losses under low wind is equal to 7.40%.

The water application efficiency under any of the two wind conditions would remain the same for all the arrangements or layouts used under that condition provided that the infiltration capacity is not exceeded by the application rate and no deep percolation beyond the root zone occurs. Whether such assumptions practically hold true and to what extent, would be analyzed in the following section.

Evaluation of the Wind Effect on Sprinkler Irrigation

Changes in the uniformity coefficient or application efficiency, as determined in the previous two sections, could be used to indicate the effect of wind on sprinkler irrigation. However, it would seem more desirable to use as a measure of such effect criteria that would be more easily subjected to economic evaluations. One such criterion would be the amount of water required to do a satisfactory sprinkling operation. Another would be the labor required for the movement of laterals and sprinklers and a third would be the required amount of sprinkler equipment. It is the purpose of this section to express the effect of wind variations in terms of increased water waste, labor requirements, and capital investments, under different sprinkler arrangements and operation schedules.

To establish a common ground for comparison certain general principles must be established and adhered to throughout this analysis. First, the soil moisture deficiency in the root zone of the crop to be sprinkled must be supplied to all parts of the field. Since the application rate by any sprinkler system is not absolutely uniform, this means that parts of the field would have to receive more than the depth required, but no part would receive less. Second, the infiltration capacity of the soil to be sprinkled is higher than the highest rate of application encountered under all possible combinations of layouts and wind conditions. Third, amounts of irrigation water received at any spot of the field beyond the depth required are assumed as lost, not withstanding the fact that parts of this water might eventually either rise by capillary action or find their way to the ground water body. For the purpose of this study, such amounts are considered as lost. Finally, the area to be irrigated is considered as a fixed one which should be irrigated at a given interval under all situations, while the volumes of water to be used, the labor requirements, and the installations needed will vary from one situation to another.

For a farmer using sprinkler irrigation in the Bekaa four alternative practices might be followed. In the first he would select the layout (12 x 12 meters) with the highest uniformity coefficient under low wind conditions and operate his sprinklers continuously under both low and high wind conditions. Since the minimum rate of application during the period of high winds would be lower than that during low winds the setting time that covers the high wind period would have to be longer in order to obtain uniform water application.

The second alternative would be to plan his settings so that he would use the layout best suited for low winds (12 x 12 meters) during periods of low winds, and that for high winds (8 x 10 meters) during periods of high winds. This would necessitate a change of spacings when the high wind periods set in.

The third alternative would be to adopt the layout best suited for high winds (8 x 10 meters) all through the day, under both low and high wind conditions. This, by applying higher rates of application, would require a shorter setting time than the previous alternatives, but would require a larger investment in equipment and more labor.

The fourth alternative would be to use the layout best suited for low wind conditions (12 x 12 meters) but to irrigate only as long as low winds prevail. The sprinklers would not be operated during the high wind periods. Such periods would be used for moving laterals, resting pumps, and performing other odd maintenance requirements. Such an alternative would require a larger investment in equipment.

Each of these four alternatives will now be evaluated in terms of water, labor, and equipment requirements. To establish the bases for comparison between these four alternative practices and a standard or check condition of no wind, the following assumptions are formulated:

1. The standard wind condition is assumed to be the same as the typical average low wind condition synthesized. The wind here is considered to have no effect on the water distribution from the sprinkler. The distribution would be the same as shown in figure 10. Such condition would be used as a check with which other alternatives could be compared and evaluated.

2. The high wind condition occuring is assumed to be the same as the typical average high wind condition synthesized.

The water distribution under this condition would be the same as that shown in figure 11. Based on the limited data obtained and for convenience of analysis, these high winds would be assumed to occur in the afternoon and for a duration of 5 hours. The actual determination of the probability of occurance and duration of high winds in the Bekaa requires a long record of wind velocities and a statistical analysis both of which fall beyond the scope of this study.

3. The remaining time of the day is assumed to have average low winds where the water distribution would be typically the same as that shown in figure 10.

4. The layouts to be used would be those worked out on the basis of high uniformity coefficient and considered suitable for the synthesized typical wind conditions.

5. The crop to be sprinkled is assumed to be sugarbeets with an average peak consumptive use of 8 millimeters per day under Bekaa weather conditions. The actual minimum amount of water to be added to the root zone per irrigation is thus assumed 80 millimeters based on an irrigation interval of 10 days.

6. The unit area to be irrigated is assumed to be a rectangular field 480 meters by 120 meters or 57.6 dunums. Each lateral line is assumed to be 120 meters.

7. The sprinkler system used is one with portable laterals and a fixed main.

Design procedures for the four alternatives as well as for the check being similar, only the detailed one for determining the water requirement, number of laterals and sprinklers, length of setting, and number of lateral movements for the standard wind condition is shown. Under this condition where no high winds are assumed to occur, the 12 x 12 meter layout is adopted as the best suited. By using this layout the water application would be the same as that shown in figure 15. The minimum rate of application is equal to 7.42 millimeters per hour. Therefore the length of setting required to store a minimum of 80 millimeters in the root zone would be equal to $\frac{80}{7.42} = 10.75$ hours. This leads to two settings per day with 1.25 hours for moving laterals following each setting. The length of the field is 480 meters. Therefore the number of laterals required to cover the field in the scheduled 10 day interval is equal to $\frac{480}{2 \times 12 \times 10}$* = 2 laterals. Dividing the length of laterals by the spacing between the sprinklers, the number of sprinklers required is found to be 20. The total number of lateral movements would be 40 per complete irrigation, based on having 2 laterals, 2 settings a day, and a 10 day irrigation interval. Under such an arrangement, the volume of water discharged from the sprinkler heads per setting is 20 x 2.80 x 10.75 or 448 m^3, and the total per field would be 20 x 448 or 8960 m^3. This

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* 2 x 12 x 10 are 2 settings per day, 12 meters covered by each lateral, 10 days interval.

amounts to an average application depth of 8960/57600 or 155 millimeters giving an application efficiency of 80/155 x 100 or 52%. It should be observed that had the average application rate been used rather than the minimum the setting time would have been reduced to 9.4 hours and the efficiency increased to 60%.

Under the first alternative, the high wind period would have to be included in the day time setting as mornings and evenings are the convenient normal times for lateral movements. Since the minimum rate of application is only 3.99 millimeter per hour under high winds, the day time setting would have to be extended a period of 2.25 hours to apply the same depth of water as in the check. This results in having only 0.25 hours for moving the laterals which is not adequate. Therefore to maintain the same irrigation interval and apply the same minimum quantity, the sprinkling equipment should be increased by 10%, resulting in covering the field in 18 settings instead of 20 settings as in the check. The water requirement would also be increased by 10% over the check, and the time for moving the laterals would no longer be fixed, but would shift by 2.25 hours every day. On those two days when the lateral moving time coincides with the high wind period, a saving of 0.75 hours per setting would be effected.

The second alternative, namely that of using the low wind layout under low winds and the high wind layout under high winds, is not a practical alternative that could be evaluated. Since the high wind period is shorter in duration than the length of setting, it would not be possible to effect a change in both lateral and sprinkler spacings to achieve the highest uniformity of application under high wind conditions. Even if the time of setting were to be shortened, to coincide with the high wind period, this alternative would remain impractical since it would require serious additional equipment to allow the change of both sprinkler and lateral spacings in the normal change-over time. Furthermore the actual setting time, because of the unsimilar overlap conditions under the different settings, could only be determined by trial and error. Such lengthy determination, in the light of the alternative's impracticability, was deemed unnecessary.

Third alternative would require a lateral spacing of 10 meters, and sprinklers spaced at 8 meters. To do the same irrigation job, this would require a setting time of 6.6 hours under high winds and 6.5 hours under low winds. Thus three settings per day would be used with 19.6 hours of operation per day or 1.9 hours less than the check. The length of laterals required to cover the field in 10 days would thus be reduced by 20% over the check, while the number of sprinklers would increase from 20 to 24. The volume of water delivered would be (2 x 6.5 + 6.6) x 2.080 x 24 x 10 = 9600 m^3, resulting in an application efficiency of 48%. The labor requirements would be increased by 12/10 or 20%. The pump capacity would be increased by 20%.

Under the fourth alternative, sprinklers would be operated daily for 17.75 hours only, leaving the high wind period as time for pipe moving and odd maintenance and the normal 1.25 hours for lateral movement. Due to less daily hours of operation, the sprinkler equipment would have to be increased by 20%, including the pump and main line capacity. Labor and water requirements would remain the same as for the check.

CONCLUSION

Table 12 shows the summary of the previous analysis of requirements. Rather than express requirements in absolute terms or even on a unit area basis, the figures given are in percent of the check. Although these data were calculated for a given specific area under certain assumed condition, there is no reason to believe that the relative values would differ for changed but reasonable assumptions. From this table it is possible to get an overall picture of the effect of wind under each alternative.

Under the first alternative, where sprinkling is carried on with no special provision for reducing the wind effect, the efficiency is reduced by 9% and the equipment requirements are increased by 10%. The hours of operation per day are increased by only 1%.

Under the third alternative, where the spacing between laterals and sprinkler heads is reduced, the efficiency is reduced by 6.6%. Part of the requirement - the length of laterals - is reduced by 20% while the other - heads and main line and pump capacities - is increased by 20%. The hours of operation are decreased by 7%.

Under the fourth alternative, where sprinkling is

Table 12. The relative equipment, water, and labor requirements of alternative sprinkling practices in the Bekaa expressed as percentages.

Alternative Practices	Equipment Requirements				Water Requirements		Labor Requirements
	Length of Laterals	Number of Sprinklers	Pump and Main Line Capacity	Actual Daily Hours of Operation	Volume	Efficiency	
Standard or Check	100	100	100	100	100	100	100
1st Alternative	110	110	110	101	110	91	100
3rd Alternative*	80	120	120	91	107	93.4	120
4th Alternative	120	120	120	83	100	100	100

* Second alternative was found practically unsuitable.

stopped during periods of high winds, the efficiency is maintained at the standard level, but the equipment requirements are increased by 20%. The hours of operation are decreased by 17%.

The labor requirements are not affected for the first and fourth alternatives but are increased by 20% for the third.

Since no alternative shows a definite apparent advantage in all aspects of the analysis it would seem necessary to evaluate each of the requirements in a common unit of expression. This evaluation is usually expressed in monetary units, allowing comparison of the total requirements. It is hoped that such an evaluation, using actual current prices and wages, would be executed in the near future. Then it would become possible to select the most economical alternative. However it should always be remembered that the alternatives evaluated in this study are those possible with a given sprinkler head operating under, again, a given pressure. Variations in both sprinkler type and pressures should be studied and in turn incorporated into similar layout analysis before a truly final recommendation could be formulated. This study has, however, set the pattern for such future studies the results of which would prove to be of significant value to the Bekaa farmers.

SUMMARY

This study was conducted as an attempt to evaluate the effect of winds commonly occurring in the Bekaa on the performance of sprinklers. The two main concerns in this work were first to determine the effect of winds on the uniformity coefficient and water application efficiency under defferent lateral and sprinkler spacings, and second to evaluate such effect in terms of extra water, labor, and equipment requirements as reflected under different alternative practices in the Bekaa.

Field tests were carried out to determine the actual water distribution patterns of a given sprinkler head under a fixed pressure and during periods of varying wind conditions. Simultaneous observations of wind velocities were recorded. Two representative typical wind conditions were selected. The first is an average low wind condition with an average wind velocity of 3.5 kilometers per hour. The second is an average high wind condition with an average wind velocity of 18.0 kilometers per hour. The water distribution patterns obtained under each condition were synthesized to produce a typical average distribution pattern. The two synthesized distribution patterns were tested by the uniformity coefficient under different sprinkler and lateral spacings in order to

select the best suited spacing under each condition. A 12 x 12 meter spacing was found to be the best suited under low wind condition resulting in a uniformity coefficient of 93.90%. The same spacing, tested under high wind condition, gave a uniformity coefficient of 80.39%. The best suited spacing under high wind conditions was found to be 8 x 10 meters resulting in a uniformity coefficient of 92.60%. The same spacing gave 91.60% as a uniformity coefficient under low wind conditions.

The water application efficiency for the water distribution under low and high wind conditions was determined as percentage of the total water applied at the sprinkler head. A value of 62.50% was attained under low wind and 55.10% under high wind. The 7.40% difference representing a 20% increase in losses was attributed to the increased evaporation and drift losses caused by high winds.

Evaluation of the wind effect in terms of water, labor, and equipment requirements was carried out under the different alternative practices that a Bekaa farmer using sprinklers might adopt. These alternatives are first to use the low wind 12 x 12 meter layout under both low and high wind conditions, second to use the low wind 12 x 12 meter layout under low winds and the high wind 8 x 10 meter layout under high winds, third to use the high wind 8 x 10 meter layout under both low and high winds, and fourth to use the 12 x 12 meter layout under low winds only and stop operating select the best suited spacing under each condition. A 12 x 12 meter spacing was found to be the best suited under low wind condition resulting in a uniformity coefficient of 93.90%. The same spacing, tested under high wind condition, gave a uniformity coefficient of 80.39%. The best suited spacing under high wind conditions was found to be 8 x 10 meters resulting in a uniformity coefficient of 92.60%. The same spacing gave 91.60% as a uniformity coefficient under low wind conditions.

The water application efficiency for the water distribution under low and high wind conditions was determined as percentage of the total water applied at the sprinkler head. A value of 62.50% was attained under low wind and 55.10% under high wind. The 7.40% difference representing a 20% increase in losses was attributed to the increased evaporation and drift losses caused by high winds.

Evaluation of the wind effect in terms of water, labor, and equipment requirements was carried out under the different alternative practices that a Bekaa farmer using sprinklers might adopt. These alternatives are first to use the low wind 12 x 12 meter layout under both low and high wind conditions, second to use the low wind 12 x 12 meter layout under low winds and the high wind 8 x 10 meter layout under high winds, third to use the high wind 8 x 10 meter layout under both low and high winds, and fourth to use the 12 x 12 meter layout under low winds only and stop operating under high winds. The requirements for each alternative were related to a standard or check condition where no high winds are assumed to occur.

The second alternative was found practically unsuitable because of its strict limitations. The requirements for the other alternatives were expressed in percent of the check. A comparison of such requirements showed that the wind variations caused an average reduction in efficiency ranging from 6.6 to 9.1%, while the equipment requirements, to do a certain job, were increased from 10 to 20%. The labor requirement was increased 20% under one alternative only. From these results, however, it was not possible to select the most economical alternative, because no one showed a definite advantage in all aspects. To make such a selection possible, an economical evaluation should be carried out to express all the requirements in a common monetary unit. It is hoped that such a study would be forthcoming.

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