PRESSURE VARIATION AS A MEANS OF REDUCING WIND EFFECT ON WATER DISTRIBUTION FROM SPRINKLERS

By

GHAHREMAN GHODRATNAMA

Approved:

Salim W. Macksoud: Professor of Irrigation.
In charge of Major.

H. D. Fuehring: Associate Professor of Soils.

A. H. Sayegh: Assistant Professor of Soils.

W. W. Worzella: Professor and Chairman of Graduate Committee

Date Thesis is presented: April 18, 1966.

PRESSURE VARIATION AS A MEANS OF REDUCING WIND EFFECT ON WATER DISTRIBUTION FROM SPRINKLERS

By

GHAHREMAN GHODRATNAMA

A THESIS

Submitted to the

AMERICAN UNIVERSITY OF BEIRUT

In partial fulfillment of

the requirements for the

degree of

MASTER OF SCIENCE IN

AGRICULTURE

April 1966

SPRINKLERS AND WIND

GHODRATNAMA

ACKNOWLEDGEMENT

I wish to express my sincere gratitude to Professor Salim W. Macksoud for his encouragement and guidance throughout the study and for his efforts in the correction of the manuscript.

Thanks are also due to Miss Seta Havounjian for typing this manuscript.

Ghahreman Ghodratnama

ABSTRACT

This study was carried out to determine whether variations in the operating pressure of a sprinkler irrigation system could be used to reduce the undesirable effects of strong varying winds on such systems.

Field tests were carried out to determine the actual distribution pattern of a single sprinkler head under various conditions of wind and pressure. These data were then used to produce synthesized or generalized distribution patterns under each possible combination of 20, 40 and 60 psi and low and high wind condisions. The application rates resulting from various layouts under the tested combinations of pressure and wind were determined by means of a geometric summation technique. This technique was compared to actual application rates and was found to be lower by about 10%.

The uniformity coefficients and application efficiencies were obtained for each layout and the selection of the most suitable systems was based on the product of these two-(the overall efficiency). However the infiltration capacity of the soil was also a decisive factor in such selection. Among the selected layouts it was observed that it was possible to improve the overall efficiency of two layouts- 12x12 meter and 12x14 meter both rectangular and triangular- by increasing the operating pressure from 40 to 60 psi with the advent of strong winds. However an economic evaluation of such procedure indicated that the costs of the extra power required to produce the higher pressure was more than the saving in water and fuel resulting from efficient operations of the system. Improvement in efficiencies amounting to at

least 20% would be required before such increase in pressure would become economical. Actual improvements ranged from 3 to 6% only.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure		Page

I. INTRODUCTION

Increased agricultural production is essential for meeting the growing demand for a higher standard of living throughout the world, particularly in underdeveloped countries. The use of irrigation to increase crop yields is not a new technique, but hitherto surface irrigation methods have been favored in many countries because of the prevailing economic conditions. These conditions are changing, largely as a result of increased industrialisation. Sprinkler irrigation, which is already widely used for supplemental irrigation in the humid areas of the world, is becoming a more common method of irrigation in arid and semi-arid countries.

Paramount among the many advantages claimed for sprinkler irrigation over the surface methods, are its higher uniformity of application and efficiency. However the achievement of high efficiency and uniform water distribution is controlled by various conditions. The presence of daily wind variations is one of the important factors limiting sprinkler performance. To overcome this, setting lateral lines at right angles to the prevailing wind, decreasing the spacing between sprinklers and between laterals and interrupting sprinkler operation during the windy periods have been suggested and evaluated by many workers.

At the present time little sprinkler irrigation is practiced in the Bekaa Plain of Lebanon, because of the fear of the adverse effect of wind on the water distribution pattern, and the high initial cost of sprinkler systems. If enough evidence can be obtained to show that sprinkler irrigation can be more economical and more efficient than surface methods under certain conditions, then wide spread use of sprinklers can be expected when these conditions prevail.

So far, the effect of winds commonly occurring in the Bekaa on the performance of sprinklers under a fixed pressure, and the effect of these winds on the cost of irrigation by sprinklers under a variety of alternatives in the same area have been evaluated. However the simultaneous effect of wind and pressure variation on sprinkler efficiency and uniformity has not been studied yet. It is the purpose of this study:

1. To determine the influence of varying wind conditions on the distribution pattern of a given sprinkler head operating under different pressures.
2. To investigate the possibility of utilizing variations in operating pressures as a means of reducing the undesirable influence of windy intervals on the efficiency of sprinkler irrigation, and
3. To evaluate such pressure variation considering its benefits in relation to the increased cost it requires.

II. REVIEW OF LITERATURE

According to the experience of many countries, many of the advantages presented by sprinkler irrigation over conventional systems are minimized by nonuniform winds, which greatly reduce its efficiency especially as far as uniformity coefficients and water losses are concerned. Several measures have been studied to reduce the negative effects of wind, such as pressure variations and the setting of sprinklers in such a way to avoid interference by wind. It is the purpose of this chapter to review the available literature on the effect of wind and pressure on the performance of sprinkler systems.

A. Sprinkler Distribution Pattern, Uniformity Coefficient and Water Application Efficiency.

The pattern of water distribution from one sprinkler head is circular in shape, and the amount of water applied to an area decreases as the distance from the sprinkler increases (39). In order to obtain a reasonable uniformity of application, water from several sprinklers must be added to the same area (33). The degree of uniformity obtainable depends primarily upon the design of the sprinkler, the spacing of sprinklers, the pressure at the nozzles, and the state of prevailing winds (13). The criterion used for studying distribution patterns of sprinklers is the uniformity coefficient formula (14). There are several defining formulas, but the one commonly used is that of Christiansen (18):

$$CU = 100(1 - x/mn)$$

in which: CU is the uniformity coefficient in percentage, "x" is sum of deviations of individual observations from the mean value "m", and "n" is the number of observations. An absolutely uniform application is then represented by a uniformity coefficient of 100 per cent; a less uniform application by some lower percentage. The drawback of this formula according to Benami and Hore (6) is that it depends upon the average deviation of the readings from the mean, and that the average deviation is not a satisfactory measure of performance.

Basically similar expression was developed by Wilcox (39):

$$U = 100 - 100\ SD/M$$

where:

U = the uniformity coefficient, in percentage form

SD = the standard deviation of the total depths of water

M = the mean of these depths

Here again Benami and Hore (6) believe that although squaring the deviations gives added weight to extreme readings, this coefficient does not adequately differentiate between a satisfactory and an unsatisfactory distribution pattern.

Another uniformity coefficient is that suggested by Benami and Hore (6) themselves. This expression is in the form of:

$$A = 166(2\ Ta + Da\ Ma)/(2Tb + Db\ Mb)\ .\ \frac{Na}{Nb}$$

where:

Ma is the mean of the group of readings above the general mean

Mb is the mean of the group of reading below the general mean

Na and Nb are the number of readings above and below the general respectively.

Ta is the sum of the readings above Ma

Tb is the sum of readings below Mb

Da is the difference between the number of readings below and above Mb (for the group above the general mean)

Db is the difference between the number of readings above the below Mb (for the group below the general mean)

The Soil Conservation Service of the United States Department of Agriculture suggests the ratio of 25 percent of the observation having the least values over the average depth of catch as uniformity coefficient (9).

Water application efficiencies can be considered as a basis for evaluating both sprinkler and surface methods of irrigation (20, 29). Water application efficiency may be defined as the ratio of the quantity of water effectively put in the crop root zone and utilized by growing crops to the quantity delivered to the field, the efficiency being expressed as a percentage (18, 30). It is expressed in the following formula:

$$Ea = (Ws/Wf \times 100)$$

where:

Ea is the water application efficiency,

Ws is the amount of water stored in the root zone during the irrigation

Wf is the amount delivered from the sprinkler nozzles in case of sprinkler irrigation (37).

The ratio of the minimum depth of catch to the computed depth for the average discharge of all the sprinklers on a lateral has been proposed by the Soil Conservation Service as an application efficiency for the lateral (9).

There are several factors involved in determing water application efficiency, one of them being water losses (40). The losses during irrigation may be due to evaporation losses from the surface of flowing water, or evaporation in the air by sprinkler nozzle spray, losses to deep percolation and/or runoff from the field (11). Water application-losses with a properly designed sprinkler irrigation system are limited to drift, evaporation losses in the air from the sprinkler spray, evaporation from the soil surface during irrigation, and possibly, evaporation from the intercepting leaf surface and some percolation (29). The factors either directly or indirectly affecting drift and evaporation are droplet size, air temperature, wind velocity, relative humidity, and application rates (11).

A proposal by Hansen (18) has been made to determine the efficiency of a given sprinkler system on the basis of its actual performance. He proposes a distribution efficiency to be used in place of application efficiency. The proposed formula for water distribution efficiency which can be used to evaluate the degree to which the water is uniformly distributed is:

$$W.D.E. = (1-y/d)$$

where:

W.D.E. = water distribution efficiency

y = average numerical deviation in depth of water stored in any spot from the average depth stored during the irrigation

d = average depth of water stored during the irrigation (16).

Bagley and Hansen (4) introduced a new concept of application efficiency considering both uniformity coefficient and water application efficiency by multiplying these two factors. This efficiency is called overall application efficiency and according to Woodward (40) is a good indication of sprinkler performance. It will be utilized in this study.

Effect of Wind on Sprinkler Performance

One of the advantages claimed for sprinkler irrigation over surface irrigation is its high uniformity of water application. Other than the design of the system, its operating pressure, and the type of sprinkler used, wind is the factor that affects the coefficient of uniformity most adversly (18, 19, 20, 25, 31, 33, 40). To overcome this, Israelsen (18) suggests setting the lateral lines at a right angle to the prevailing wind direction and decreasing the spacing between sprinklers and between lateral lines as much as forty percent. Kovern (19) agrees with Israelsen in that the spacing must be reduced in proporation to the amount of wind if any good distribution pattern is to be retained. According to Wilcox (38) the best distribution is obtained by rectangular spacings with sprinkler spaced more closely together at right angle to the direction of the wind. Thorne and Peterson (36) have also suggested the use of closer spacings for solution of wind problems. To eliminate the effect of wind on the uniformity of water distribution from the sprinkler, establishment of wind breaks is suggested by Abd-El-Sami (1).

Hamilton and Shrunk (15) also suggest laterals to be placed perpendicular to the normal prevailing wind direction, but they believe that the benefits from such a plan are dependent on the regularity of wind direction. To improve uniformity under windy conditions, Hamilton (15) recommends closer sprinkler distances, triangular spacing of sprinkler heads and the use of special nozzles.

To minimize the wind effect Woodward (40) suggests the following percentages:

Wind conditions	Lateral spacings
No wind	65% of the wetted diameter
5 mph or less	60% of the wetted diameter
5-10 mph	50% of the wetted diameter
Over 10 mph	22-30% of the wetted diameter

Schwab and Frevert (32) recommended sprinkler spacings of .3 to .5 of the wetted diameter, and lateral spacings of .5 to .7 of the wetted diameter.

Mutayreh (26) for a RainBird No. 30 and a pressure of 40 psi recommends a 12 by 12 meter rectangular spacing being best suited under low wind conditions encountered in the Bekaa Plain of Lebanon. This gave a uniformity coefficient of 93.90%. Under what he considered high wind conditions and the same pressure a spacing of 8 x 10 meter resulted in a uniformity coefficient of 92.69 percent. Working on water application efficiencies he got a value of 62.5 percent under low wind and 55.10 percent under high wind conditions with a pressure of 40 psi.

The use of triangular arrangements in windy areas rather than the rectangular ones to compensate for unfavorable effect of high wind on the distribution has been suggested by McCulloch (24). According to Bauzil (5) a triangular layout equal to 55 to 60% of the wetted diameter of the sprinkler head used would generally give a uniformity coefficient much higher than that resulting from a square layout under similar conditions. Good results in overcoming the unfavorable effect of wind on the distribution pattern obtained from a triangular layout at 60 percent of the wetted diameter were reported by Selim and Nicola (34).

The following results were obtained in an experiment carried out by Bagely and Hansen (6) using a double nozzle sprinkler (13/64" x 1/8") at 40 psi.

Spacing	30' x 50'	40' x 50'	30' x 60'	40' x 60'
Wind mph	4.2	2.2	3.4	4.4
Uniformity coefficient	85	92	88	81
Water application efficiency	90	96	92	89
Overall-efficiency	77	88	81	72

It is seen from the table that under high wind overall efficiencies are lower than those under low wind, however for similar wind conditions overall efficiency is lower under larger spacings (4).

Kovern (19) stated that Christiansen made the following conclusion after studying the effect of speed of rotation, spacing of sprinklers, and wind upon distribution patterns: "although the patterns appear very uneven, the effect of wind on the uniformity of distribution over a larger area, with sprinklers close enough together to provide an adequate overlap, is less serious than unevenness from other causes, such as variation in rate of rotation, because with wind 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 and produce an exaggerated effect".

It is Gray's (14) belief that although, certain measures can be taken to reduce the effect of winds such as- changes in sprinkler nozzles and spacings of laterals, sprinklers and layouts- changes mean additional equipment, and extra cost. Furthermore, he believes that the delay involved in making changes may also cause a decrease in crop yields, due to lack of water during critical growing periods.

The Effect of Pressure on Sprinkler Performance

Sprinkler systems operate under a wide range of pressure from 5 psi to over 100 psi (25). The desirable pressure depends upon power costs, area to be covered, type of sprinkler used, sprinkler spacing and crop being irrigated (21).

Sprinklers in the low-pressure range (5-30 psi) have a small area coverage and relatively high precipitation rates for recommended spacings (40). Generally, there are two areas that receive maximum application rates, one close to the sprinkler and the other further out, resulting in poor overall distribution of water (39). Low pressure sprinklers are adapted to small acreages where gravity pressure can be utilized. Their use is confined to soils with intake rates of over $\frac{1}{2}$ inch per hour (40). Medium-pressure sprinklers (20-50) cover large areas and have a wide range of precipitation rates. The water droplets are well broken up (25). High pressure sprinklers (50-100 psi) cover large areas and precipitation rates for recommended spacings are high (12). Distribution patterns are easily disrupted by wind because of higher water trajectory (19). They have high-application rates above 1/3 inch per hour, and their wetted diameter is from 120 to 230 feet (40).

Under high pressure the streams issuing from nozzle jets are broken up into much finer spray with correspondingly greater surface area than under lower pressures (39). In this case both evaporation losses and wind drift losses are increased (16). Frost and Shwalen (11) believe that in general these losses are about proportionate to nozzle pressure. Increasing the pressure from 40 to 50 psi, they stated, will give an increase of 1/5 in spray losses. Losses are highest under moderate and hot weather conditions (40). Wilcox (39) indicated that pressures higher than 30 psi are not desirable. At higher pressures, according to him, the trajectory is higher and more of the spray hits the trees. It is also his belief that at higher pressures there is a greater wear on the sprinkler. On the other hand he reports that at pressures below 20 psi the water is not distributed uniformly enough, and on the whole the pressures of 20 to 30 psi are most suitable for under tree use.

To assure reasonably uniform distribution of water over the entire area, differences in pressure at the sprinklers should be kept to a minimum (25). A common rule, which should be adhered to as closely as practical, is, to limit pressure differences along a sprinkler lateral to 20 percent of the higher pressure (25). To accomplish this, Woodward (40) suggests that portable lines be run on the contour where feasible. Pressure in each line is regulated by the valve opening to it. In some cases a portable line will run uphill or downhill, thus causing wide variation in pressure. Various methods are in use for overcoming these difficulties, such as partial stops or valves along the portable line, or different sized sprinkler nozzles, or better still a small valve under each sprinkler (40).

Duffee (10) in a study on low pressure sprinkler irrigation concluded that a pressure of 20 psi is the lowest pressure that can be used and insure reasonable pressure at all sprinklers. According to him such a low pressure sprinkler system can be used on reasonably level areas, and that elevation differences which effect sprinkler pressure will not be serious in a line not over 200 or 300 feet long. Carreker (8), from an experiment made in Georgia, concluded that a fairly good distribution of water was obtained under calm periods at 40 psi. Wind velocities, even as low as 2 to 3 mph cause some distortion to the distribution pattern. The maximum diameter of throw was approximately 120 feet from the single nozzle operating at 40 psi.

Considering discharge and the area covered, many workers (8, 14, 19, 25) believe that both the quantity of water discharged and the area covered increase with greater pressures. Furthermore increasing the pressure tends to give more uniform sprinkler patterns (40). According to Wilcox (39) the time required to apply one inch of water to an area covered by one sprinkler setting is shorter for the lowest and highest pressures. The reason for this is that the area covered increases more rapidly than the rate of increase of discharge up to a certain point, then the reverse condition exists. Unfortunately no study has been made on the simultaneous effects of wind and pressure on sprinkler performance. This may be due to the difficulties involved in interpreting the data obtained from such experiments.

Cost of Sprinkler Systems

The total cost of a sprinkler irrigation is made up of fixed and variable costs. Fixed costs comprise initial investment, interest on investment, amortization of the system, and taxes and insurance (3). Variable costs are those of power, labor and miscellaneous (7, 23, 39).

Initial investment, being the cost of equipment and other installations,depends on many factors such as size of farm, crop and soil characteristics, source and location of water, depth of pumping, and type of power units (10, 16, 18, 25, 34). Initial investment in a portable sprinkler system is about LL 700 per hectare in Lebanon according to Nadjafi (28). Interest rates on irrigation projects are usually figured at 5 percent of the average values of the system which is half of the original purchase price (17). Scott (33) assumes a period of 10 to 15 years as a basis for amortising sprinkler systems. As for taxes, generally 2% of the average investment is allowed to cover property taxes and insurance (23). Using aluminum pipes and fittings, annual fixed costs for a 5 hectare farm conditions in Lebanon is 912.60 (26).

Labor costs for moving sprinkler laterals will vary considerably depending on the spacing arrangement, moving procedure for the type of equipment involved and the efficiency of both management and labor (33). The layout of the system can also affect these costs (3). In Lebanon, in 1964, labor requirement for sprinkler irrigation varied from 1.9 to 11.7 man-hours per irrigation per hectare (28).

The other factors controlling cost of sprinkler irrigation systems are:

1. Soil type. The effect of soil type on the cost of a sprinkler system is that it controls the rate of application which in turn controls the number and the size of laterals (37).

2. Hours of operation. Hours of operation per day controls the amount of water applied and the number of laterals needed to cover a given size of farm. Changes in the amount of water applied or the number of laterals to be used will bring about changes in sprinkling cost (37).

3. Irrigation frequency. The higher the frequency of irrigation the higher will be the labor cost (33). And besides, the loss of water will become more in the case of light and frequent irrigation practices resulting in higher irrigation costs (14, 23).

4. Wind. To overcome the adverse effect of wind on sprinkler performance it is usually suggested to run the lateral lines across the wind and place the sprinklers closer together. Closer spacings of sprinklers results in more costly systems (25).

5. Type of system. Different costs will result from water application by different sprinkler systems (2). The permanent systems involve a large investment in distribution pipes and sprinklers and for that reason are, in general, confined to very intensive farm units (18). Portable systems, on the contrary, require a much smaller investment, but a considerable amount of labor is involved in the necessary moving of the equipment (15). In Lebanon, due to the relatively low labor costs, portable sprinkler systems are more economical than solid ones. The initial costs of solid systems are very high, and the annual cost

per hectare is 138 percent more than that of portable systems (28).

6. Relative land elevations which control the size of main lines and the size of pumping units (13).

7. Land slope, which controls the location of the main line and the length and size of the laterals (13).

III. MATERIALS AND METHODS

This study consisted of two parts. In the field tests were run on the distribution patterns of single and multiple sprinkler head installations under different pressure and wind conditions. These data were then used in the office to synthesize typical general distribution patterns.

Field Experimental Set-Up

These tests were run on the Agricultural Research and Educational Center of the American University of Beirut situated in the Bekaa Plain. Most of the tests were made between September 5 and October 7, 1964, and a few between September 10 and 15, 1965.

The experimental layout is shown in Figure 1. Water was pumped from a reservoir with a centrifugal pump and discharged through the sprinkler head. Excess water could be diverted back to the reservoir. Two pressure gages were used for measuring the pressure in the system. One was included in the pipe system while the other- a pitot tube type- was used to measure the pressure at the sprinkler nozzle. Valves A and B were used to control the pressure and flow in the system. Tin cans, 7.5 centimeters in diameter and 5.5 centimeters deep were placed in a 2x2 meter grid pattern on a level area, and the sprinkler to be tested was placed in the center of the pattern. The cans were set level and fixed in the soil to prevent overturning by wind. They were distributed over an area larger than that wetted by the sprinkler under all wind and pressure conditions.

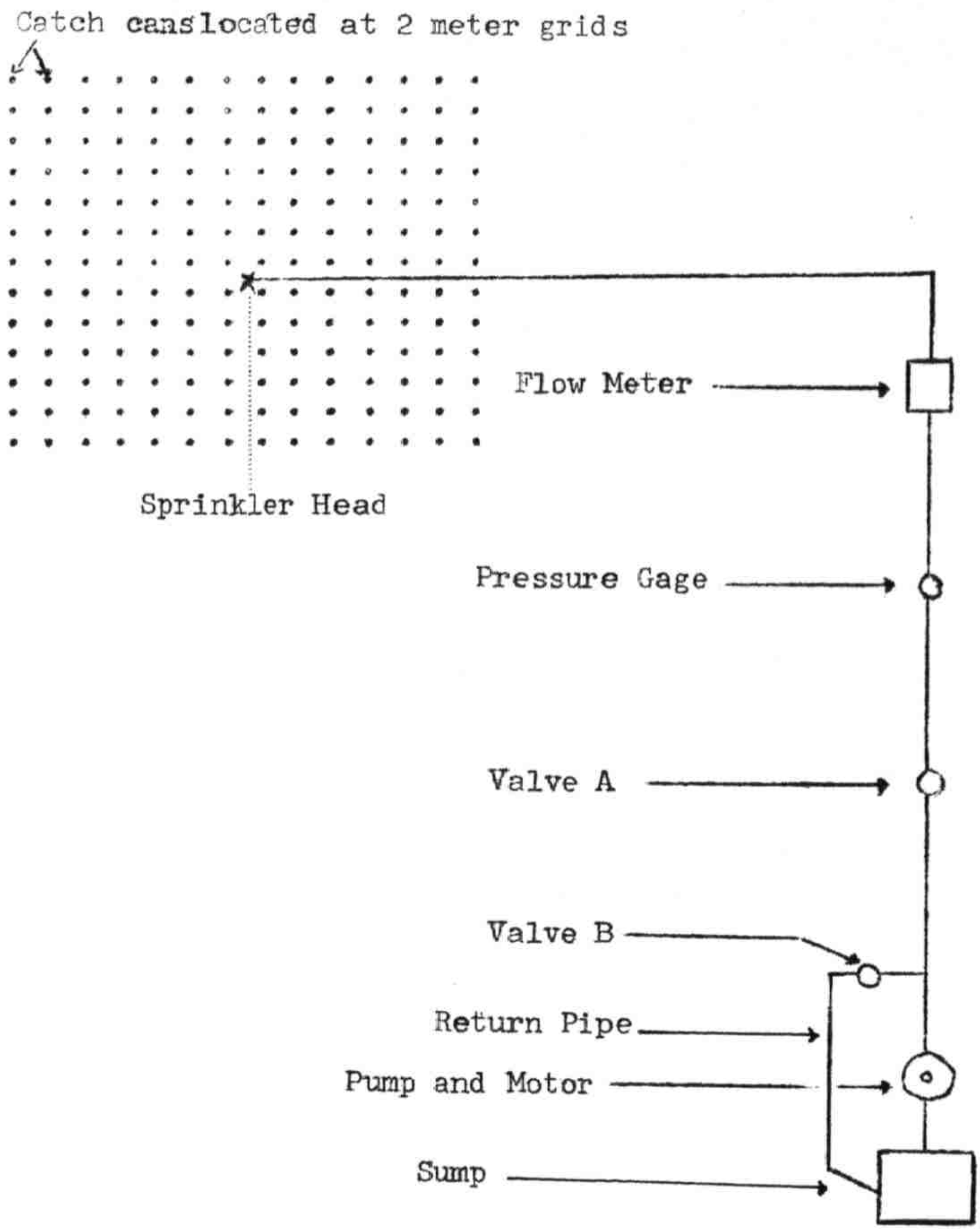

Figure 1. Schematic field set-up for determining distribution pattern using a single sprinkler head.

The sprinkler head, used had the following specifications:

Name of manufacturer	Rain Bird Sprinkler Manufacturing Corporation, Glendora, California
Model	30
Number of nozzles	2
Nozzle sizes	3/16" abd 3/32" at 7^{o}.
Rated discharge	8.0 gallon per minute at 40 psi

Before running the tests the system was operated to check its performance. Then it was run for periods of three hours under different possible combination of wind and pressure. A total of forty tests were made divided equally between 20 and 60 psi pressure. Of the low pressure tests 8 were run under low wind conditions, 6 under medium and 6 under high winds. Of the high pressure tests 5 were run under low winds, 6 under medium and 9 under high winds.

The pressure for each trial was kept constant by manipulating valves A and B and regulating the back flow to the reservoir. The discharge from the sprinkler head was measured by a flow meter reading in gallons. After three hours, water was shut off, and the catch in each can was measured using a graduated cylinder and recorded.

Wind Speed Measurements

While the sprinkler was operating wind speed measurements were made using a 4 cup cumulative type anemometer. Readings were taken every two minutes for half hour periods sometimes separated by short intervals spent checking the operation of the sprinkler system.

A similar procedure was followed in operating three sprinkler heads placed along a lateral, as is shown in Figure 2. The

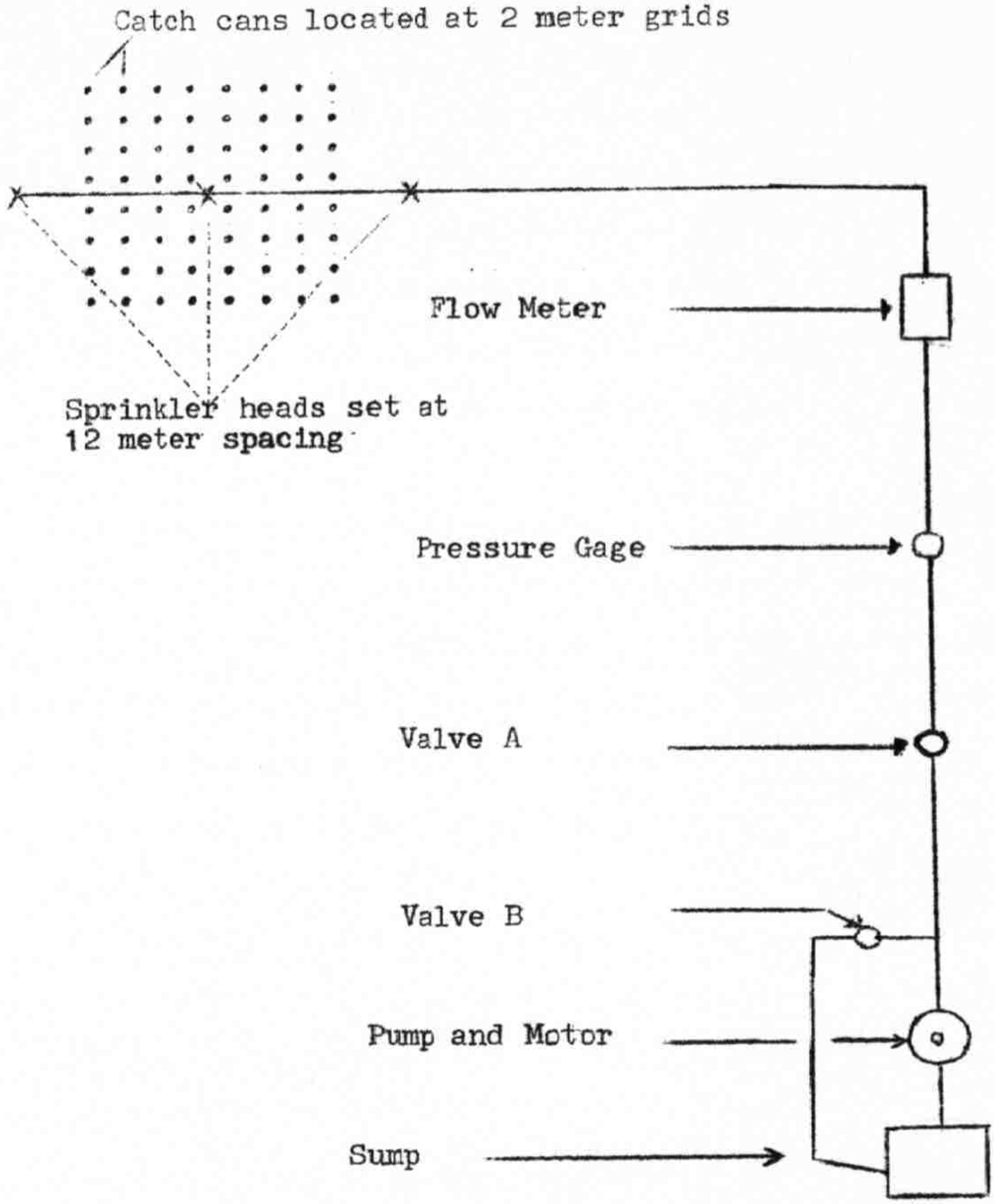

Figure 2. Schematic field set-up for determining distribution pattern using three sprinkler heads.

simultaneous wind speeds were also recorded.

Processing of Data

The recorded field data for each trial were converted to application depths in millimeters per hour, by dividing the volume of catch by the area of the can and by the time of run. Charts were prepared showing the distribution of the various measured depths with respect to the sprinkler head. Two millimeter lines of equal application rates were drawn, assuming uniform variations between adjacent measurements.

The differences between the readings of the anemometer recorded every two minutes were multiplied by 30 to give wind velocity in kilometer per hour. The average wind speed for each test was calculated by averaging all the wind speeds recorded during the time the experiment was running. The variation of wind speed with time was also plotted on the chart showing the lines of equal application rates.

Then, on the basis of the shape of the lines of equal application rates, wind variations with time and average wind velocities during each experimental period, four patterns were selected as typical for each of the combinations of 20 and 60 psi pressure and low and high wind conditions.

The four patterns so selected were then averaged to produce a synthesized general water distribution pattern for the given wind and pressure conditions.

The same procedure was applied to the data for the three sprinkler head arrangement, except that no averaging was carried out for lack of sufficient trials.

IV. RESULTS AND DISCUSSION

Wind and Pressure Influence on Distribution Patterns of a Single Sprinkler

The field trials, as described under Materials and Methods, were actually conducted under three wind conditions namely- low, medium, and high. Only a few of the trials show a water distribution pattern under a fixed wind velocity, because of the rarity of such stable conditions. Therefore two average wind conditions were considered. The first was a low wind condition occurring in the mornings in which the winds did not seem to affect the uniformity of water application from the sprinkler head. The second was a relatively high wind condition occurring in the afternoons and distorting the water distribution pattern considerably.

Out of the many trials carried out 16 were selected to represent these two dominant and typical wind conditions in the Bekaa Plain (four for any combination of pressure and wind conditions). The remaining trials represent water distribution under transitional wind conditions- from low to high wind. It would have been difficult to consider all possible wind variations because of the time limitation. Therefore only these two dominant wind conditions are considered hereafter.

From studying the various application charts it was arbitrarily decided to consider periods with an average wind speed not exceeding four kilometer per hour and with a maximum speed not exceeding eight kilometer per hour as periods of low winds. For periods of high winds the average was to be not less than twenty kilometers per hour. The trials selected to represent the actual distribution obtained under low wind conditions, and under 60 psi pressure are represented in Figures 3, 4, 5 and 6. The figures shown are depth of application in millimeter per hour received at each catch can. The two millimeter equal water application lines were drawn. Tables 1, 2, and 3 show the recorded wind velocities for these trials. The velocities are in kilometers per hour averaged during each two minutes. The average wind speed during each test period was calculated by averaging velocities for each two minutes, and was 2.68, 3.31, 1.78 and 0 kilometers per hour respectively. In all these tests the range of wind velocities was between 0 and 8 kilometers per hour.

In order to analize the distortion caused by wind variations on the sprinkler performance, it was necessary to have a distribution pattern under theoretically no wind conditions. This is practically considered similar to the average low wind condition described above. Then by keeping this as a check, the effect of high wind on the distribution patterns could be evaluated. On this basis, the four typical patterns obtained under low wind conditions were synthesized to produce a standard water distribution pattern. This pattern is shown in Figure 7 and can be considered as typical distribution under theoretically no wind conditions.

Similarly a generalized distribution pattern under high wind conditions and 60 psi pressure was obtained. This is shown in Figure 8. Four trials were selected to represent actual water distribution under low wind conditions and 20 psi. The generalized pattern obtained from these trials is shown in Figure 9, while that for 20 psi and high wind conditions is shown in Figure 10. For distribution patterns under 40 psi, the data prepared by Mutayreh (20) were used. Figures 11 and 12

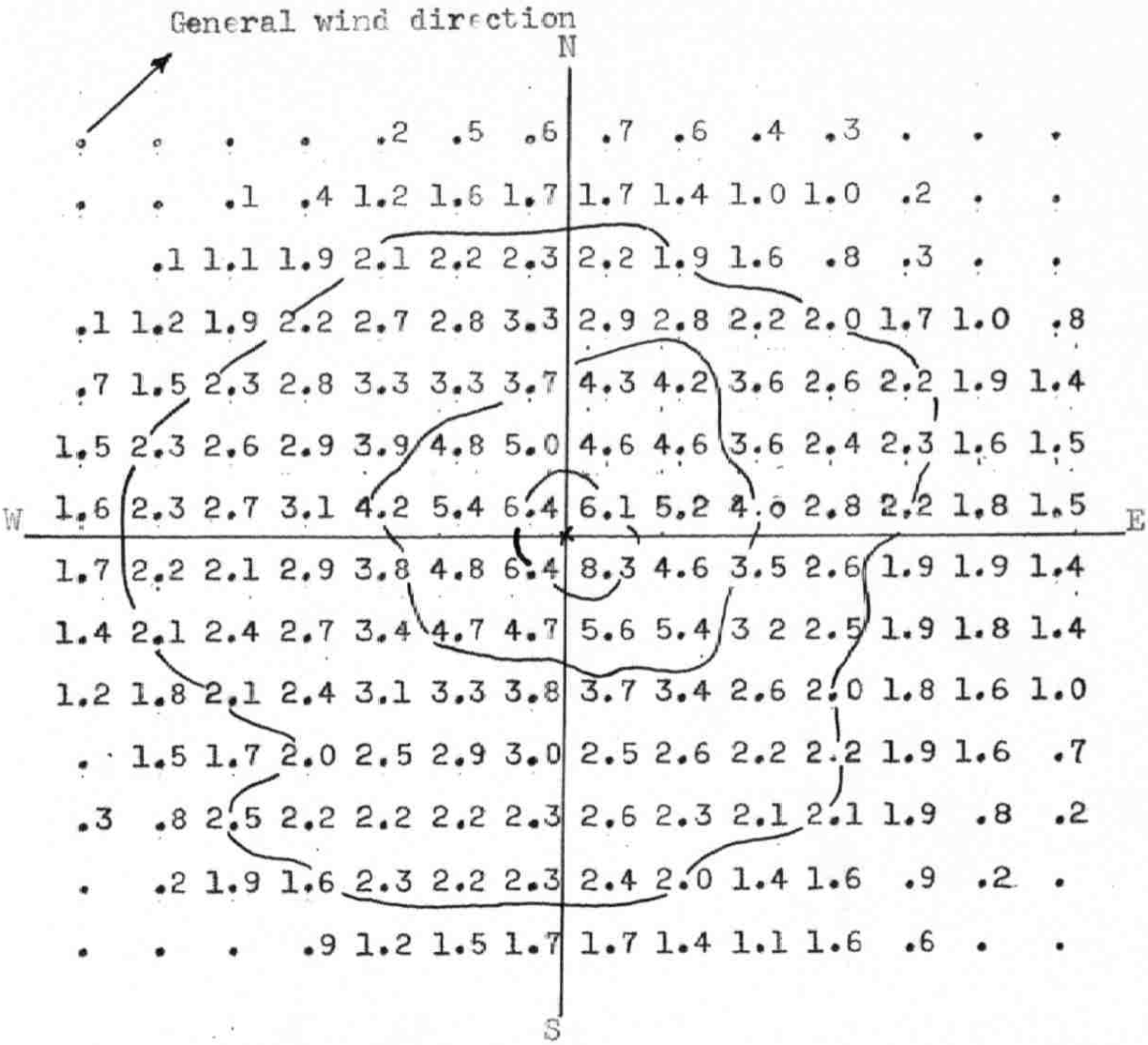

Figure 3. Distribution pattern for a single sprinkler head under low wind conditions and a pressure of 60 psi- Test No. 6, 6 to 9 AM, September 10, 1964.
Figures shown are depth of application in millimeters per hour. The 2 millimeter water contours are superimposed. Points represent decimal points as well as location of catch cans.

Table 1. Observed wind velocities for test No. 6.

Operating time min.	Average wind velocity km/hr.	Operating time min.	Average wind velocity km/hr.
30	3.6	88	1.2
32	6.0	90	0.6
34	3.3	92	0.3
36	2.4	94	0.9
38	3.3	96	0.6
40	3.0	98	0.8
42	4.2	xxxxxx	
44	3.6	130	2.4
46	4.8	132	0.9
48	3.6	134	1.2
50	4.5	136	0.9
52	4.2	138	0.3
54	3.6	140	2.7
56	3.3	142	3.3
58	3.6	144	4.5
60	3.0	146	0.6
62	3.6	148	2.7
64	3.3	150	3.6
66	3.3	152	2.4
68	2.7	154	4.5
70	2.7	156	2.7
72	3.3	158	2.1
74	2.4	160	0.0
76	3.6	162	1.5
78	2.4	164	3.6
80	2.1	166	3.6
82	1.5	168	1.8
84	0.6	170	2.7
86	0.9	172	3.0
		Total	150
		Average wind velocity	2.68

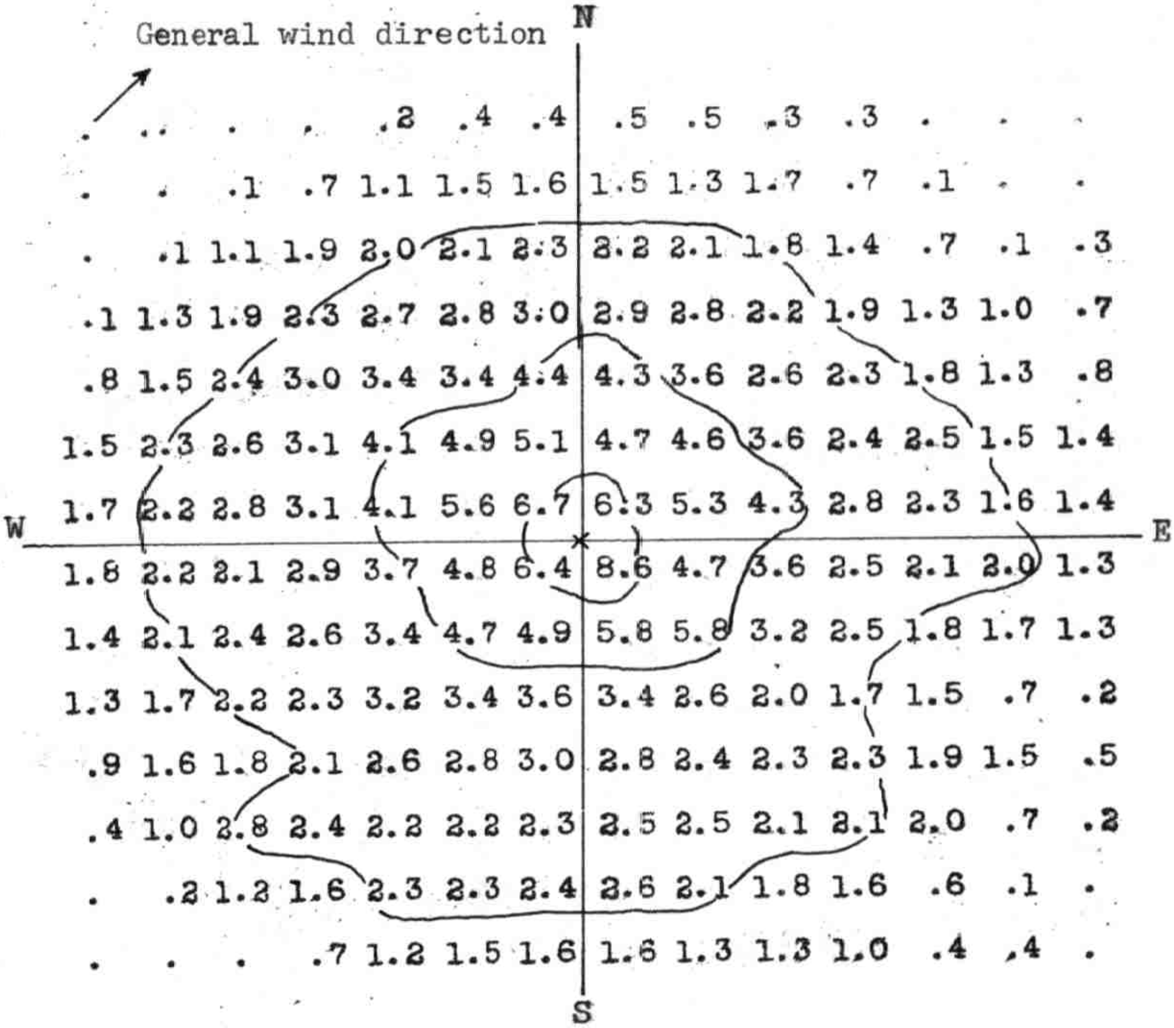

Figure 4. Distribution pattern for a single sprinkler head under low wind conditions and a pressure of 60 psi. Test No. 11, 6 tp 9 AM, September 11, 1964.
Figures shown are depth of application in millimeters per hour. The 2 millimeter water conttours are superimposed. Points represent decimal points as well as location of catch oans,

Table 2. Observed wind velocities for test No. 11.

Operating time min.	Average wind velocity km/hr.	Operating time min.	Average wind velocity km/hr.
32	5.1	106	0.6
34	8.1	108	0.3
36	4.5	110	1.5
38	3.3	112	2.1
40	4.2	114	5.4
42	4.2	116	2.1
44	5.4	118	0.0
46	5.1	120	1.5
48	5.1	122	4.5
50	6.3	124	3.6
52	4.8	126	3.3
54	6.0	128	2.1
56	5.7	130	3.3
58	4.8	132	1.2
60	4.5	134	1.5
62	4.8	136	1.2
64	4.2	138	0.6
66	4.8	140	3.6
68	4.5	142	4.5
70	4.5	144	6.0
72	3.9	146	0.9
74	3.9	148	3.9
76	4.5	150	4.8
78	3.3	152	3.3
80	4.8	154	0.6
82	3.0	156	3.6
84	2.7	158	2.7
86	2.1	160	0.0
88	0.9	162	2.1
90	1.2	164	4.8
92	1.5	166	4.8
94	0.9	168	2.4
96	0.6	170	3.6
98	1.2	172	4.2
100	0.0	Total	229
102	0.6		
104	3.6	Average wind velocity	2.68

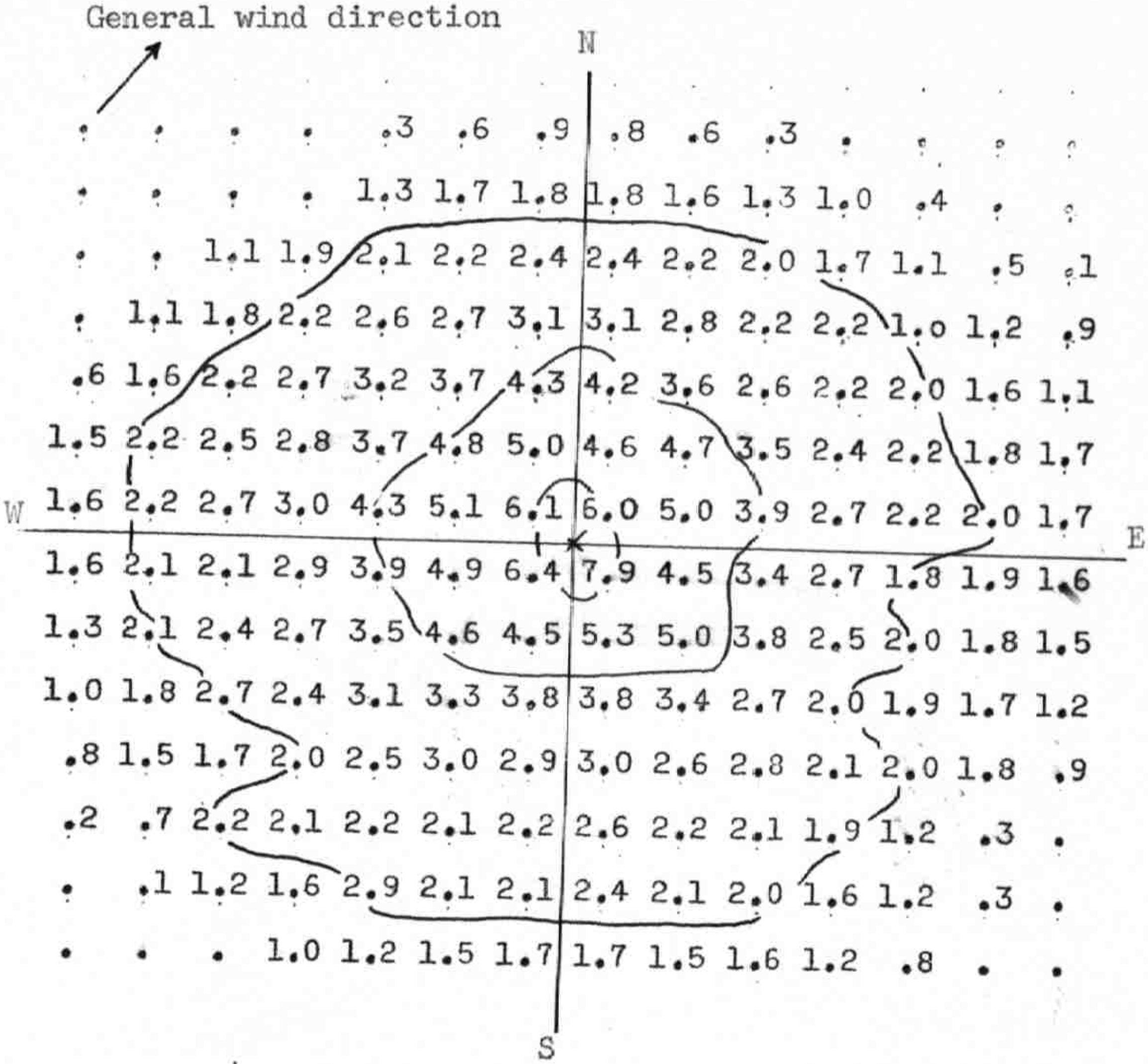

Figure 5. Distribution pattern under low wind conditions and a pressure of 60 psi- Test No. 31, 6 to 9 AM, September 18, 1964. Figures shown are depth of application in millimeters per hour. The 2 millimeter water contours are superimposed. Points represent decimal points as well as location of catch cans.

Table 3. Observed wind velocities for Test No. 31.

Operating time min.	Average wind velocity km/hr.	Operating time min.	Average wind velocity km/hr.
34	2.5	92	0.6
36	4.0	94	0.9
38	2.1	96	0.6
40	1.5	98	0.3
42	2.1	xxxxxx	
44	2.1	130	1.5
46	2.7	132	0.6
48	2.7	134	0.9
50	2.4	136	0.6
52	3.3	138	0.3
54	2.4	140	1.8
56	3.0	142	2.1
58	2.7	144	3.0
60	2.4	146	0.6
62	2.1	148	2.1
64	2.4	150	2.4
66	2.1	152	1.8
68	2.4	154	0.3
70	2.1	156	1.8
72	2.1	158	1.5
74	1.8	160	0.0
76	1.8	162	1.2
78	2.1	164	2.4
80	1.5	166	1.2
82	2.4	168	1.8
84	1.5	170	2.1
86	1.5	Total	95.5
88	1.2		
90	0.6	Average wind velocity	1.78

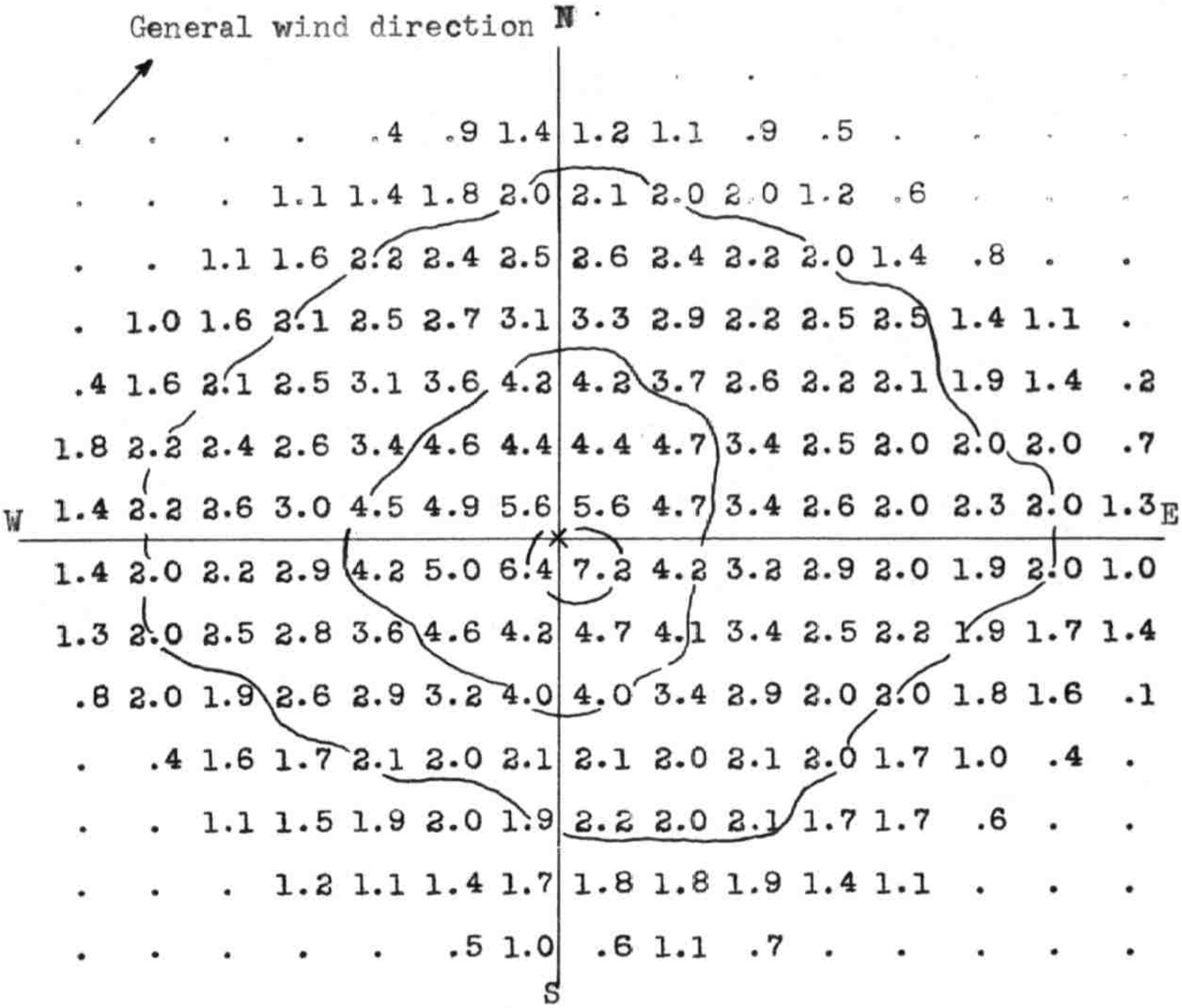

Figure 6. Distribution pattern for a single sprinkler head under low wind conditions and a pressure of 60 psi- Test No. 38, 6 to 9 AM, September 22, 1964.
Figures shown are depth of application in millimeters per hour. The 2 millimeter water conours are superimposed. Points represent decimal points as well as location of catch cans. No wind velocity was recorded by the anemometer during the test period.

show the synthesized general pattern for high and low wind conditions respectively.

Based on the synthesized patterns, distribution curves using values adjacent to the West-East axis of each chart were prepared. These values- following along the direction of the dominant winds- illustrate more fully the effect of wind and pressure on the water distribution; these are shown in Figures 13 and 14 for high and low wind conditions respectively.

It is seen from Figures 7, 11 and 13 that under pressures of 40 and 60 psi there is uniform water application under average low wind conditions. Water application close to the sprinkler is high and starts decreasing uniformly with distance in all directions. The major effect of increasing the pressure is to increase the average depth of application at any one point as well as to increase the wetted area. In general, there is a tendency for the water to be thrown higher in the air as the pressure increased. Under a pressure of 20 psi and low wind conditions (Figures 9 and 13) there is an area of maximum application rate close to the sprinkler and a second one further out, resulting in poor overall distribution of water. Under all pressure variations with low winds the lines of equal application rates are more or less circular, with enlarging diameters, the sprinkler being the common center. It can be assumed that an average depth of water equal to the average of any two consecutive lines is received by the area between these lines of equal application rates. Under a pressure of 20 psi there are two water contour lines associated with the same rate of application (Figure 9).

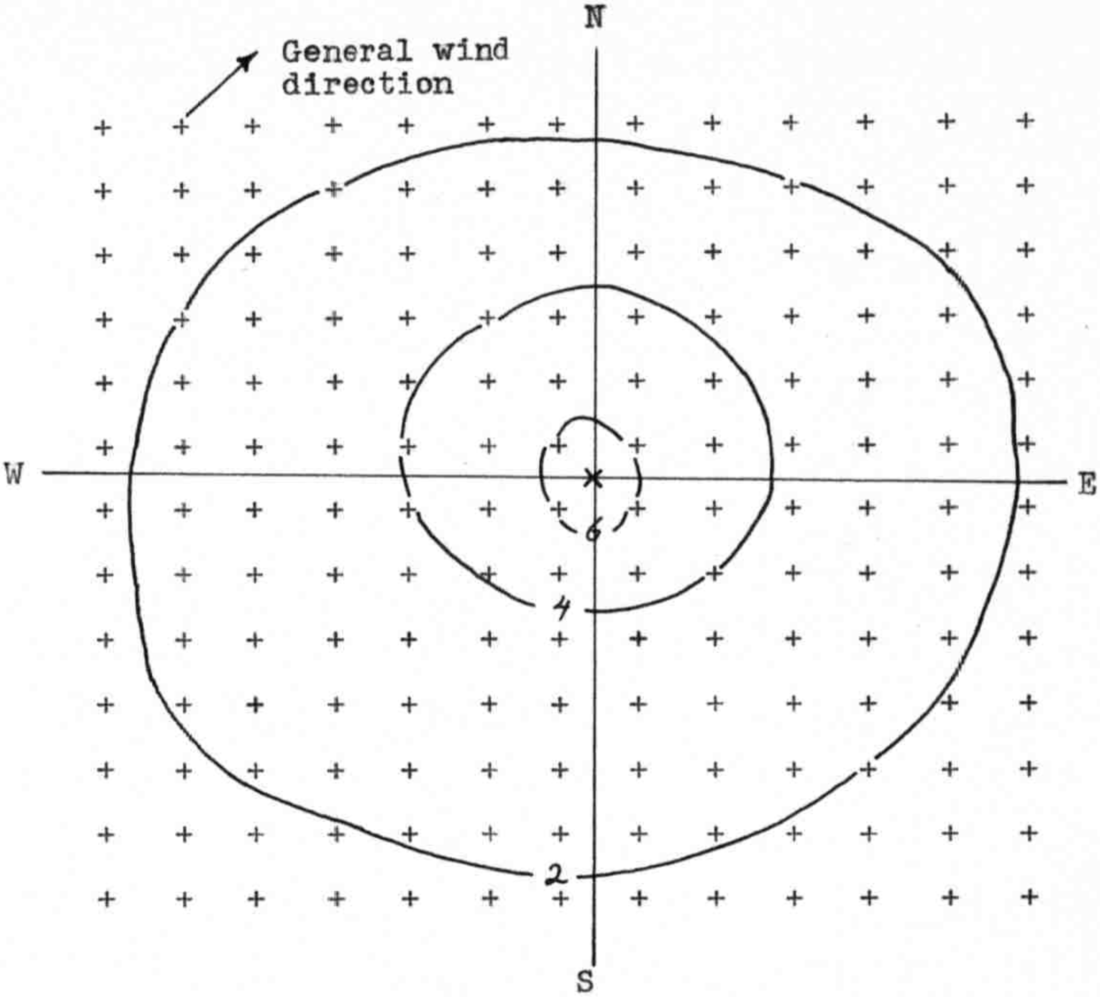

Figure 7. Generalized water distribution pattern for a single sprinkler head under low wind conditions and a pressure of 60 psi. The 2 millimeter water contours are superimposed. Grid shows location of catch cans.

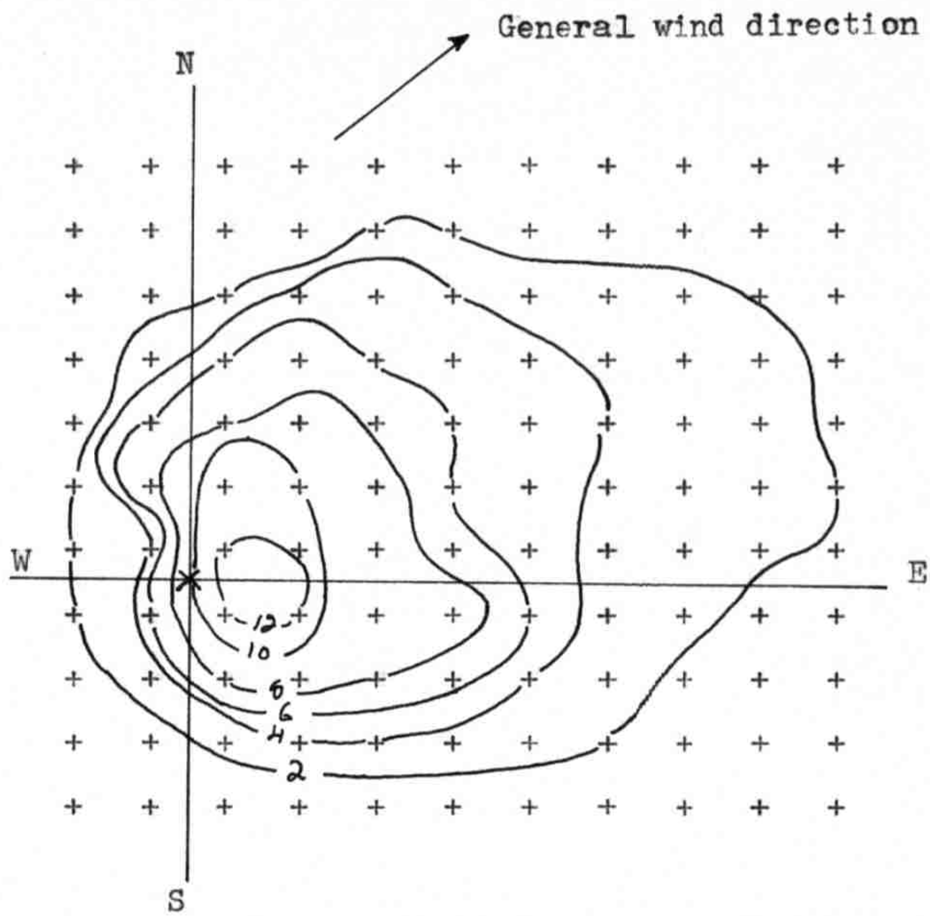

Figure 8 . Generalized water distribution pattern for a single sprinkler head under high wind conditions and a pressure of 60 psi. The 2 millimeter water contours are superimposed. Grid shows location of catch cans.

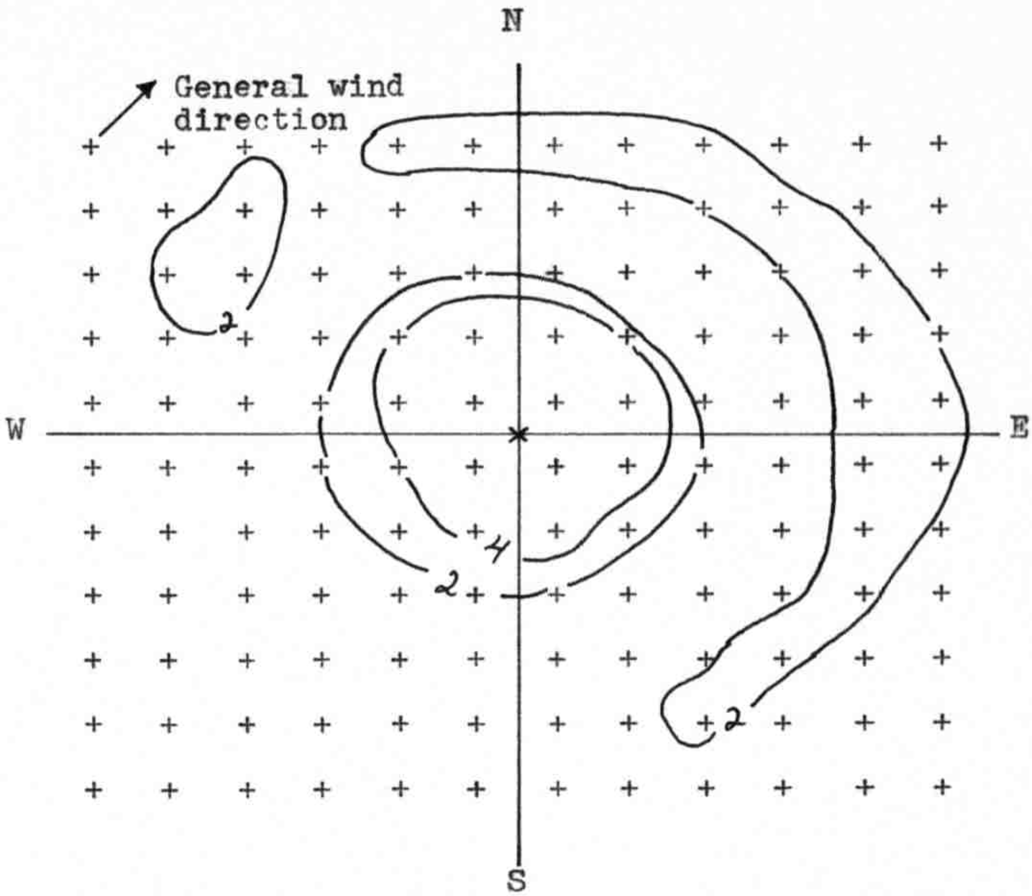

Figure 9. Generalized water distribution pattern for a single sprinkler head under low wind conditions and a pressure of 20 psi. The 2 millimeter water contours are superimposed. Grid shows location of catch cans.

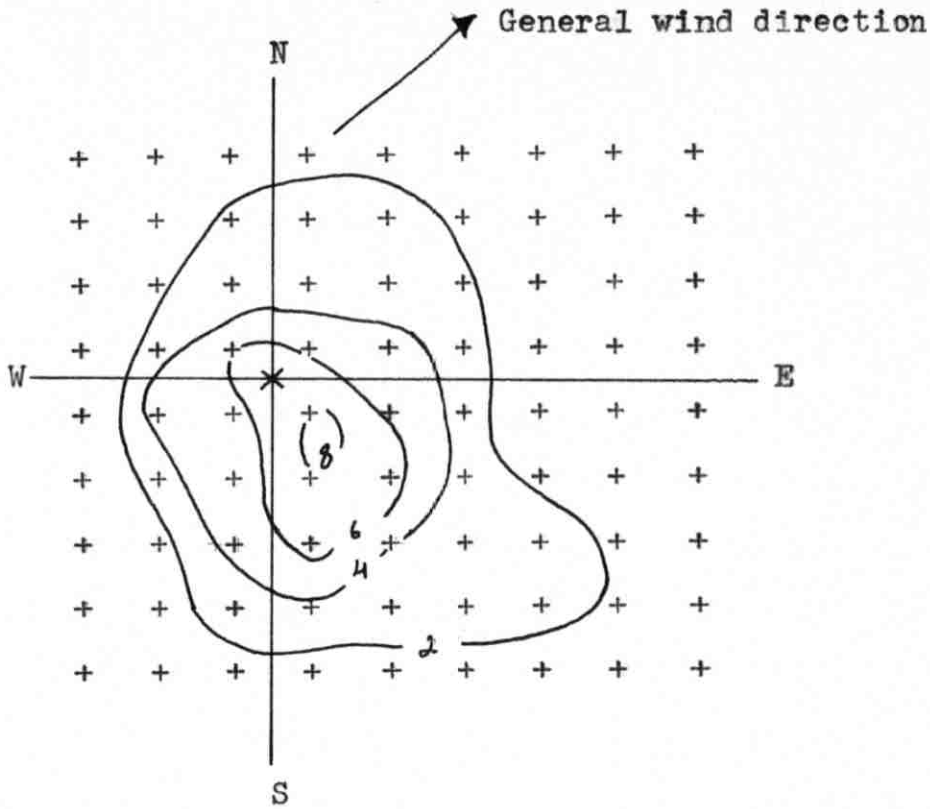

Figure 10. Generalized water distribution pattern for a single sprinkler head under high wind conditions and a pressure of 20 psi. The 2 millimeter water contours are superimposed. Grid shows location of catch cans.

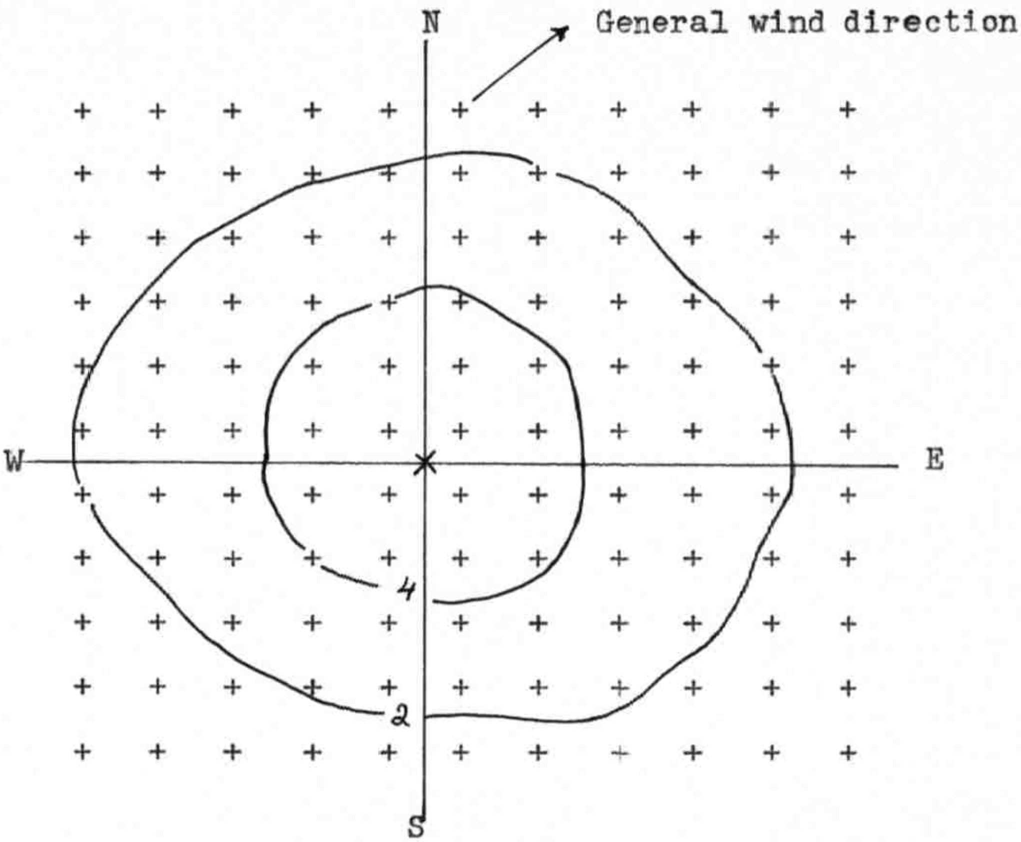

Figure 11. Generalized water distribution pattern for a single sprinkler head under low wind conditions and a pressure of 40 psi. The 2 millimeter water contours are superimposed. Grid shows location of catch cans. Taken from Mutayreh(26).

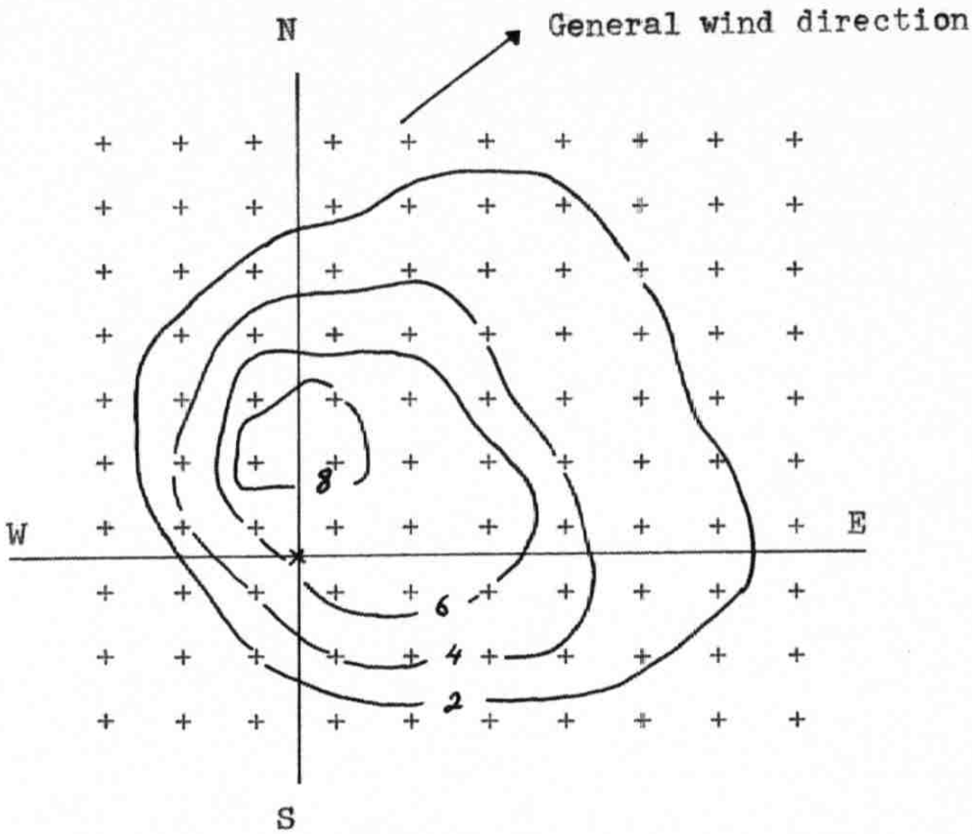

Figure 12. Generalized water distribution pattern under high wind conditions and a pressure of 40 psi. The 2 millimeter water contours are superimposed. Grid shows location of catch cans. Taken from Mutayreh(26).

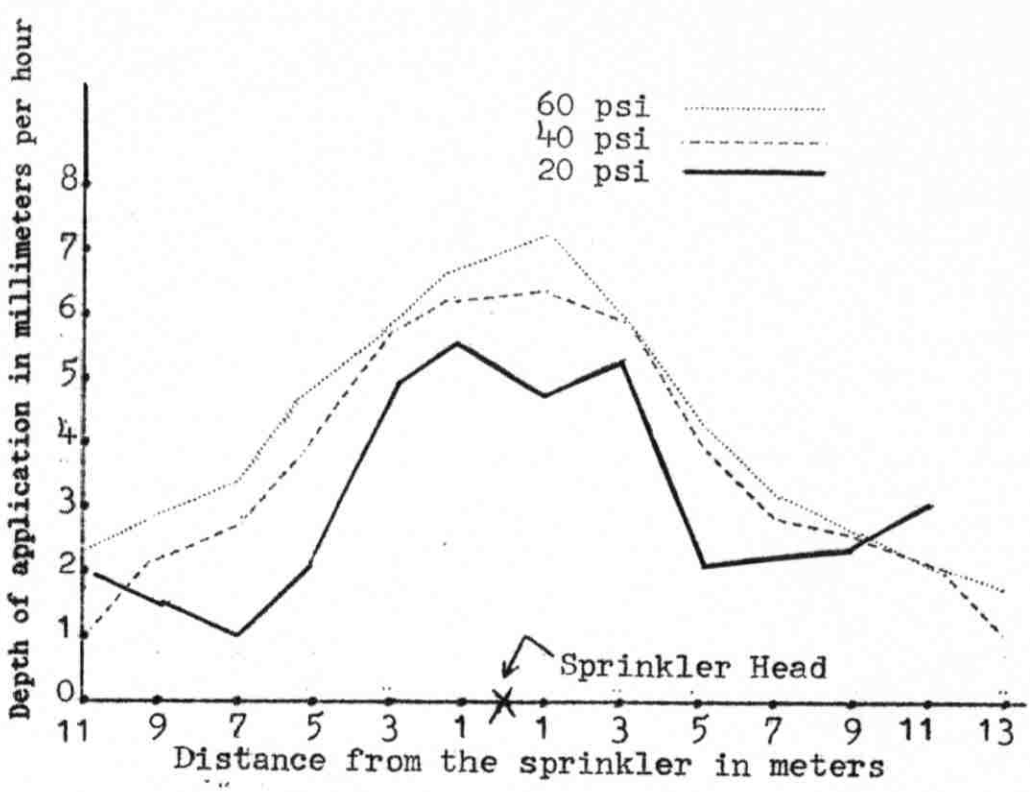

Figure13 . Variation of water application rate for a single sprinkler head under low wind conditions with pressures of 20, 40 and 60 psi.

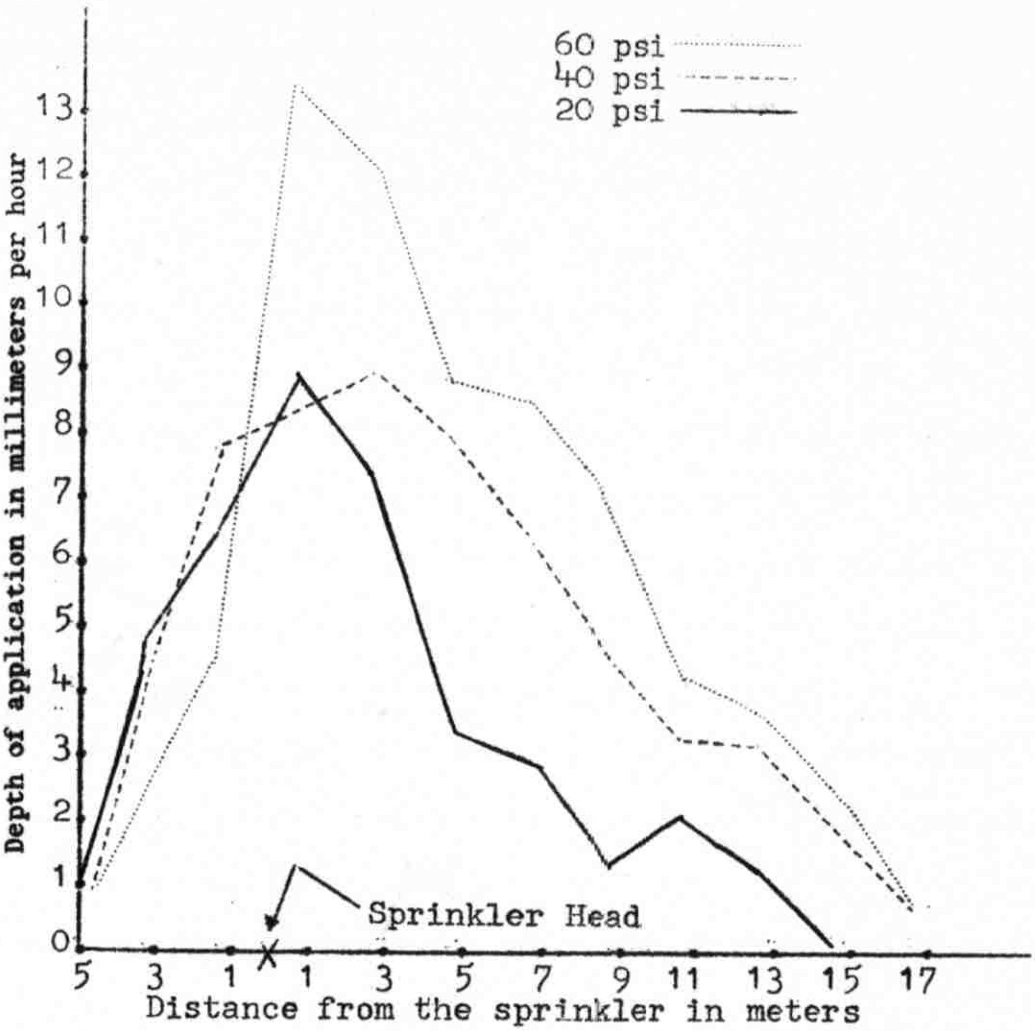

Figure 14. Variation of water application rate for a single sprinkler head under high wind conditions with pressures of 20, 40 and 60 psi.

As seen from Figures 8, 10, 12 and 14, high wind conditions distort the pattern of water distribution by sprinklers and reduce its uniformity under all pressure variations. Under high wind conditions water application conour lines are no longer circular, and the sprinkler is no longer the center of water distribution. Contour lines on the East side are much closer spaced than on the West side. In general, the spray is transferred to the leeward side. By observing the distribution curves in Figure 14 it is seen that conour lines on the wind side become closer as the pressure of the sprinkler increases. In contrast, contour lines on the leeward sides become wider as the pressure increases. Comparing distribution curves for 20 psi in Figures 13 and 14 shows that occurrence of two maximum rates of water application on each side of a sprinkler, which is a characteristic of water distribution under a 20 psi pressure and low wind conditions is eliminated on the windward side under high wind conditions. On the leeward side it is less prominent under high wind than under low wind conditions.

By comparing water distribution patterns under low conditions with those under high wind conditions under any pressure it can be noted that the wetted area under low wind is larger than that under high wind, but the ratios of area wetted under low wind to that wetted under high wind changes with pressure.

Pressure Variations and Sprinkler Efficiencies

To evaluate the effect of varying wind conditions on the distribution patterns of a sprinkler system under different pressures, the product of multiplying the uniformity coefficient by the water application efficiency was used as a criterion. This product which is called overall efficiency, was obtained for different layouts and under pressures of 20, 40 and 60 psi for low wind conditions separately, and then, for high wind conditions. The effect of these high wind conditions on the distribution patterns was evaluated by comparing these two sets of values. The layouts- spacings between sprinklers and between laterals- that gave the highest overall efficiencies were considered to be the most suitable from a theoretical point of view. However there are other limiting factors that should be considered in selecting the most suitable layouts from a practical point of view. The most important of these being the infiltration capacity of the soil and the cost of sprinkler equipment.

The rate of water application should be lower than the infiltration capacity of the soil in order to keep the evaporation losses to a minimum. An application rate higher than that of the soil infiltration capacity also leads to runoff. Therefore it is necessary to apply water at a rate equal to or less than the soil infiltration capacity, even if this reduces the uniformity coefficient.

Closer spacings will necessitate a higher initial cost in sprinkler equipment on a unit area basis. However, because of the higher application rate associated with closer spacings, the time of setting will be reduced and as such the total investment in sprinkler equipment as well as the labor requirements would have to be investigated before a decision could be reached concerning suitable layouts.

Uniformity coefficients

The distribution of water from a single rotating sprinkler is not uniform over the entire circular wetted area. 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 an approximately uniform rate of water application all over the irrigated area.

To determine the most appropriate spacings uniformity coefficients and water application efficiencies under both low and high wind conditions, and under different pressures and different spacings were calculated. Assuming sprinklers would be placed at a given spacing and that all would give identical patterns, the total accumulated application rates for any one layout were obtained by adding the depths contributed to each test area from every sprinkler. The detailed procedure for this- for a 12x12 meter spacing, under a pressure of 60 psi and high wind conditions- is shown in Figures 15, 16 and 17 and Table 4. The area bounded by sprinklers #1, #2, #3 and #4 in Figure 15 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 generalized sprinkler distribution pattern for high wind conditions and 60 psi at each of the proposed positions in Figure 15. Contributions 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

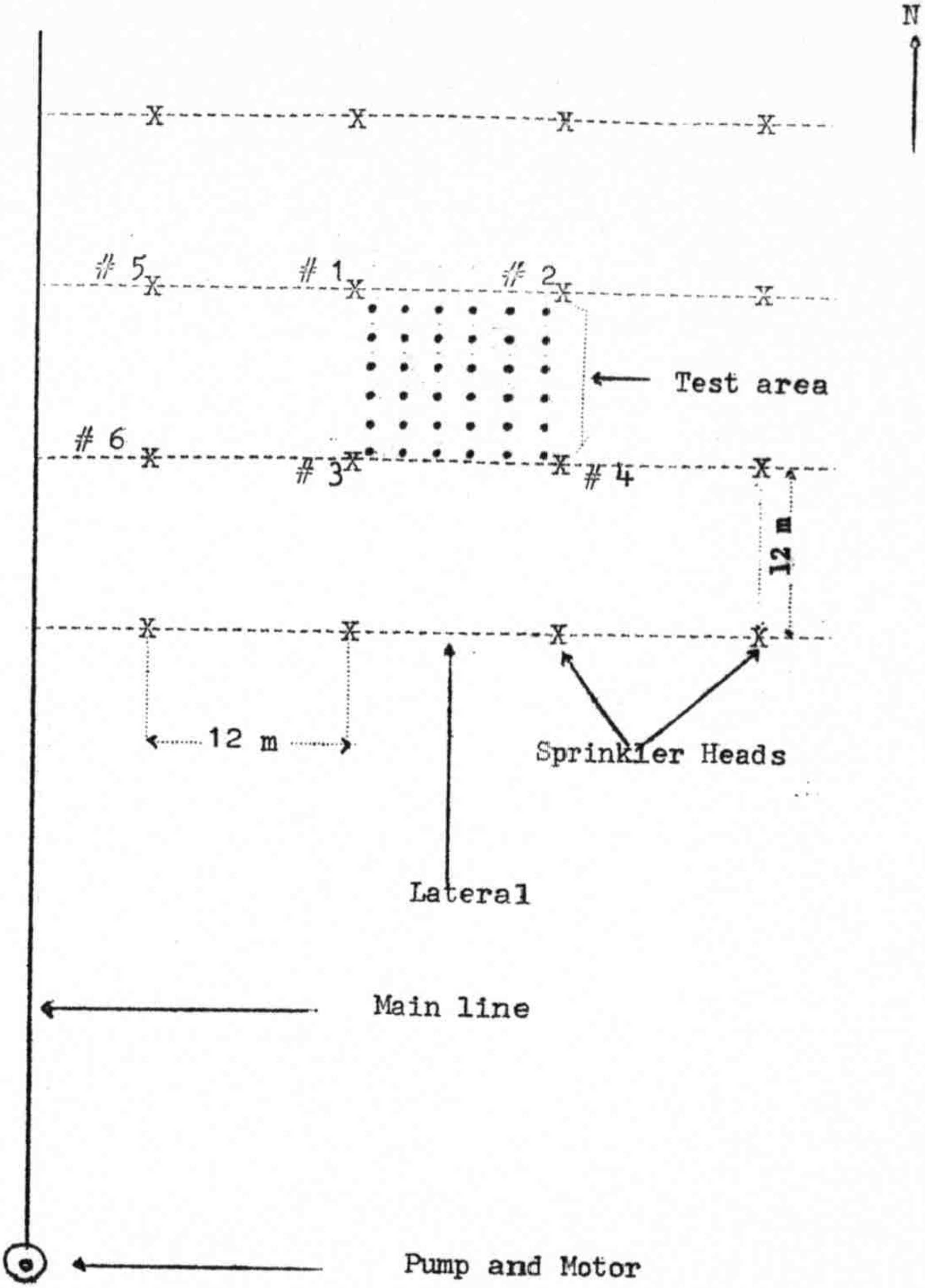

Figure 15. Plan for the proposed 12 x 12 meter layout.

1 X — 2 X

12.81 (1)	12.0	8.98	8.18	6.63	3.18
--- (2)	---	---	0.02	2.46	5.10
0.39 (3)	1.34	2.36	1.81	1.52	1.46
--- (4)	---	---	---	---	---
2.62 (5)	0.99	0.24	0.03	---	---
1.29 (6)	0.80	---	---	---	---
10.92	8.57	8.72	6.80	4.70	3.21
---	---	---	---	1.03	4.66
2.41	4.11	4.24	3.54	3.19	2.84
2.95	---	---	---	---	1.32
1.53	0.48	0.09	---	---	---
---	1.82	0.19	0.08	---	---
3.96	5.50	5.24	4.36	3.42	1.78
---	---	---	---	0.04	1.04
6.47	6.81	5.45	5.07	4.07	3.54
---	---	---	0.06	0.80	3.08
0.19	---	---	---	---	---
2.67	2.26	0.50	0.39	---	---
0.50	1.08	1.30	1.04	0.34	0.25
---	---	---	---	---	---
7.82	9.19	7.02	5.30	3.92	4.67
---	---	---	0.30	1.93	5.59
---	---	---	---	---	---
2.50	2.45	1.67	0.46	---	---
---	---	---	---	---	---
---	---	---	---	---	---
11.81	11.26	9.08	4.50	3.94	2.89
---	---	---	0.24	2.27	8.63
---	---	---	---	---	---
2.83	3.30	1.26	0.24	---	---
---	---	---	---	---	---
---	---	---	---	---	---
12.30	11.04	6.40	6.17	5.85	3.97
---	---	---	0.33	2.92	3.39
---	---	---	---	---	---
3.32	2.34	0.85	0.31	---	---

X 3 — X 4

Figure 16. Depth of water contributed by various sprinklers recorded in order corresponding their numbers as shown in Figure 15. The values are obtained from Figure 8. Spacing 12x12 meters, high wind, and 60 psi.

X X

17.11	15.13	11.58	10.54	10.61	9.74
17.31	14.98	13.24	10.42	8.92	12.03
13.29	14.57	11.19	9.49	8.33	9.44
10.82	12.72	9.99	7.10	6.19	10.15
14.64	14.56	10.34	4.98	6.21	11.52
15.62	13.38	7.25	6.81	8.77	7.36

X X

Figure 17. Summation of depth of water contributed to each point by sprinklers, as shown in Figure 16.

Table 4. Uniformity coefficent calculation for a 12x12 meter rectangular layout under high wind conditions and 60 psi pressure.

Observation	Absolute Difference		Observation	Absolute Difference
17.11	6.09		10.82	0.20
15.13	4.11		12.72	1.70
11.58	0.56		9.99	1.03
10.54	0.48		7.10	3.92
10.61	0.41		6.19	4.83
9.74	1.28		10.51	0.50
17.31	6.29		14.64	3.62
14.98	3.96		14.56	3.54
13.24	2.33		10.34	0.68
10.42	0.70		4.98	6.04
8.92	2.10		6.21	4.81
12.03	1.01		11.52	0.50
13.29	2.27		15.62	4.60
14.57	3.55		13.38	2.36
11.19	0.07		7.25	3.77
9.49	1.53		6.81	4.21
8.33	2.69		8.77	2.25
9.44	1.58		7.36	3.66
		Total	396.7	93.12

$m = 11.02$ mm/hr.

$n = 36$

Uniformity coefficient $= 100\ (1 - x/mn)$

$= 100\ (1 - 93.12/396.7)$

$= 100 - 23.47$

$= 76.53$ percent.

data obtained are shown in Figure 16. The first value in each position was contributed from sprinkler #1, the second from sprinkler #2, and so on. All the collected depths or values applied at each position were added, as shown in Figure 17. The figures shown are depth of application in millimeters per hour, that would be obtained under high wind conditions, and under 60 psi pressure and by using the 12x12 meter spacing.

To check the degree of accuracy of the geometric summation just described a separate field test was carried out. In this the accumulated catch from three sprinkler heads was actually measured under various wind and pressure conditions but one spacing. These figures were compared with the totals that would have resulted from a geometric summation using the distribution pattern of a single head under similar pressure and wind conditions. Table 5 shows a comparison of these figures. From this it is apparent that the actual catch is always higher than the geometric summation by about 10 percent. This means that the actual efficiencies might be expected to be higher by about the same amount. Uniformity coefficients will not be influenced as much as this increase is general and will be masked. The reasons for this difference lie mainly in the fact that evaporation losses from the catch cans while the sprinkler is operating are added several times when using the geometric summation method, while actually there is only one loss.

Using the figures obtained by geometric summation the uniformity coefficient was calculated by the Christiansen formula (18):

$$CU = 100(1 - x/mn)$$

where:

Table 5. Comparison of actual water application by three sprinklers to the calculated application by geometric summation

Pressure psi	Wind	Actual application mm/hr.	Geometric Summation mm/hr.	Percent increase
20	Low	3.62	3.40	6.34
	High	4.03	3.71	8.63
40	Low	5.42	5.01	8.30
	High	5.47	4.87	12.18
60	Low	6.07	5.92	6.73
	High	7.32	6.21	17.78
			Total	59.97
			Average	10.00

CU is uniformity coefficient

x is sum of deviations of individual observations in the test from the main value

m is mean value of all observations

n is number of observations

Table 4 shows the application of this formula using the data given in Figure 17.

The same procedure was followed for getting the uniformity coefficients for thirteen different rectangular and three triangular layouts, under each of the pressures used and the two wind conditions. This resulted in the 96 combinations shown in Table 6. Calculation of uniformity coefficients for triangular layouts spaced closer than 10x12 meter was avoided because of average application rates, under 60 psi, exceeding the assumed soil infiltration capacity.

Uniformity coefficients under all pressure variations were higher under low wind conditions than under high ones for all layouts, except for layouts spaced closer than 10 meters under 20 psi. Under close spacings, pressure variations did not result in appreciable differences in uniformity coefficients.

Generally, uniformity coefficients under similar wind conditions were higher under 40 and 60 psi than under 20 psi. Uniformity coefficients obtained under 60 psi, under both low and high wind conditions, were very close to those obtained under 40 psi, sometimes being a little higher and sometimes a little lower.

Triangular layouts, in general, give slightly superior uniformity coefficients to the rectangular ones.

Table 6. Uniformity coefficients under different spacings, pressures and wind conditions.

Layout	Spacings meter	Wind	20 psi	40 psi	60 psi
Rectangular	14x16	Low	72.91	85.5	88.95
		High	53.37	66.51	66.93
Rectangular	14x14	Low	69.34	91.30	90.30
		High	57.11	71.72	70.94
Rectangular	12x14	Low	69.91	92.60	91.39
		High	65.56	77.11	75.84
Rectangular	10x14	Low	76.43	90.69	91.89
		High	68.73	75.0	82.03
Rectangular	12x12	Low	75.46	93.90	91.76
		High	67.51	80.39	76.53
Rectangular	10x12	Low	77.98	92.80	92.76
		High	74.10	84.57	83.96
Rectangular	10x10	Low	76.36	93.02	93.01
		High	76.18	88.70	83.53
Rectangular	8x10	Low	81.26	91.60	93.86
		High	88.05	92.60	86.46
Rectangular	8x8	Low	82.60	97.57	93.75
		High	88.13	91.80	93.23
Rectangular	6x8	Low	89.11	97.85	97.80
		High	93.35	96.45	92.15
Rectangular	6x6	Low	87.48	98.63	96.69
		High	95.83	94.45	93.83
Rectangular	4x6	Low	92.89	97.73	97.91
		High	98.42	97.11	96.39
Rectangular	4x4	Low	97.03	98.61	99.61
		High	97.31	97.43	96.86
Triangular	12x14	Low	76.92	92.58	87.11
		High	63.40	76.90	77.42
Triangular	12x12	Low	74.42	93.1	89.23
		High	69.15	80.72	78.14
Triangular	10x12	Low	72.75	92.95	93.30
		High	78.00	85.72	85.54

Uniformity coefficients however have to be considered in conjunction with application efficiencies if they are to be used for the selection of layouts.

Water application efficiencies

Water application efficiency may be defined as the ratio of the quantity of water effectively placed into the crop root zone to the quantity delivered by the sprinkler heads to the field, the efficiency being expressed as a percentage (37).

$$Ea = (Ws/Wf \times 100)$$

The volume of water discharged from the sprinklers was measured during the experimental trials through a flow meter. Since all the factors affecting the discharge were theoretically kept constant throughout each set of trials the sprinkler discharge should have given constant values. Actually this value showed some changes. Therefore an everage of the different values, under any specific pressure, was considered as the sprinkler discharge under that pressure. Average sprinkler discharge under pressures of 20, 40, and 60 psi were 1386, 1878 and 2306 litres per hour, respectively.

The amount of water stored in the root zone was assumed to be represented by the depth of water received at the catch cans. This assumption was based on the consideration that first, water falling on the ground surface was considered to infiltrate into the soil with out runoff, and second, no deep percolation occured, i.e. water infiltrating into the soil stayed in the root zone. Also, evaporation from the can and that from the soil were considered to be similar. With the above assumption, to get the amount of water stored in the root zone, the sum of depths of water received by the catch cans was multiplied by the area represented by each can- which is four square meters. Table 7 shows the application efficiencies obtained and the data used in the calculation.

As can be seen from Table 7 column 7, water application efficiencies are higher under low wind conditions than under high ones for all pressures. This is due to the fact that at high wind velocities the fine spray was carried out beyond the collecting area and therefore failed to reach the ground surface in measurable quantities. More evaporation from the droplets occurs under high wind conditions. This is due to the wind removing the saturated air faster from around the water drops and to its breaking up of the large drops into smaller ones causing more surface to be subjected to evaporation (11).

It is generally believed that under higher pressures the streams issuing from the nozzles jets are broken up into much finer spray with correspondingly greater surface area, bringing about both increases in evaporation losses and wind drift (11). But the results obtained in this study as is seen from Table 7 show that water application efficiency under high wind conditions increases as the pressure increases, being 59.5, 61.0 and 69 percent under 20, 40 and 60 psi, respectively. This may be due to the fact that since application rates under lower pressures were lower, water in the catch cans got warmer under low pressures than under high ones, resulting in more evaporation losses. Had the trials been carried out in winter, different results may have been obtained.

Table 7. Water application efficiencies for various pressure and wind conditions.

(1) Pressure psi	(2) Wind condition	(3) Total depth of water received by the wetted area mm/hr.	(4) $\frac{(3)x4}{1000}$	(5) Water received by the soil liters/hr.	(6) Sprinkler discharge liters/hr.	(7) $\frac{(5)}{(6)} \times 100$ W.A.E. %
20	Low	228.5	0.91	914.08	1386	66
	High	206.31	0.82	825.24		59.54
40	Low	---	---	1300+	1878.13	69.22
	High	---	---	1146+		61.02
60	Low	403.48	1.61	1613.92	2305.80	70
	High	397.58	1.59	1590.32		68.97

+ Data collected by Mutayreh (26).

The water application efficiency under a given pressure, and under any of the two wind conditions will remain the same for all the arrangements or layouts used under that condition provided that the infiltration capacity is not less than the average application rate and no deep percolation beyond the root zone occurs due to extended periods of application.

Selection of Suitable Layouts

As previously mentioned, overall efficiency, first introduced by Hansen (40) is defined as the uniformity coefficient multiplied by the water application efficiency of the system. Overall efficiencies obtained in this manner under different spacings, wind conditions, and pressure variations are shown in Table 8. From this table it is observed that overall efficiencies decrease with a change from low to high wind conditions. That is, any layout is more efficient under low winds than it would be under high winds. This is to be expected because both application efficiencies and uniformity coefficients showed similar trends. It may also be observed that under both low and high wind conditions the overall efficiencies increase with increase in pressure under most of the spacings. The only exceptions being the 12x14, 12x12, and 8x8 meters layouts which do not show the above trend under low wind conditions, and only one layout- 6x8 meter- under high wind conditions.

Layouts having the highest overall efficiencies might be considered as the most suitable. However before going into such a selection, layouts which result in application rates that exceed the

Table 8. Overall-efficiencies in percent for different spacings under different pressure variations and wind conditions.

Layout	Spacings meter	Wind	20 psi	40 psi	60 psi
Rectangular	14x16	Low	48.12	59.18	62.27
		High	31.78	40.58	46.16
Rectangular	14x14	Low	45.83	63.20	63.21
		High	34.00	43.76	48.93
Rectangular	12x14	Low	46.14	64.10	63.97
		High	39.03	47.05	52.31
Rectangular	10x14	Low	50.44	62.78	64.32
		High	40.92	45.76	56.57
Rectangular	12x12	Low	49.80	65.0	64.23
		High	40.20	49.05	52.78
Rectangular	10x12	Low	51.46	64.24	64.93
		High	44.20	51.60	57.91
Rectangular	10x10	Low	50.40	64.39	65.11
		High	45.53	54.12	57.61
Rectangular	8x10	Low	53.63	63.40	65.70
		High	52.43	56.50	59.63
Rectangular	8x8	Low	54.52	67.54	65.62
		High	52.47	56.01	64.30
Rectangular	6x8	Low	58.81	67.74	68.46
		High	55.58	48.85	63.55
Rectangular	6x6	Low	57.73	68.27	67.68
		High	57.05	57.63	64.71
Rectangular	4x6	Low	61.31	67.65	68.54
		High	58.60	59.26	66.48
Rectangular	4x4	Low	64.04	68.26	69.73
		High	57.94	59.45	66.80
Triangular	12x14	Low	50.77	64.08+	60.98
		High	37.75	46.92	53.40
Triangular	12x12	Low	49.12	64.44+	62.46
		High	41.12	49.26	53.89
Triangular	10x12	Low	48.02	64.34+	65.31
		High	46.44	52.31	59.00

\+ Taken from Nadjafi (28)

infiltration capacity of the soil where the sprinkler is to be used, should be excluded. Average application rates were calculated for all layouts by averaging the depths of catch under each layout. These are shown in Table 9. Furthermore Table 10 shows the range of the application rates under various layouts. Considering the nature of soils in the Bekaa Plain, an infiltration capacity of 12.5 millimeters per hour is assumed to represent a safe average that should not be exceeded. It should be observed that under this notion of average rates, as long as average application rates are lower than soil infiltration capacities no runoff is lost. Rates exceeding this intake capacity which might occur at certain spots are assumed to runoff to adjacent spots where the application rate is inferior to the intake capacity and will infiltrate there.

Based on the above criterion all layouts applying an average of more than 12.5 millimeters per hour were excluded from further considerations, on the basis of exceeding the infiltration capacity of the soil. This leaves layouts of 8x10 meter and wider under 20 psi, 10x10 meter and wider under 40 psi and 12x12 meter and wider under 60 psi- the limit of layouts studied being 14x16 meter. An analysis of these layouts reveals that the highest absolute overall efficiency of 65.0 percent is achieved under a rectangular layout of 12x12 meter, a pressure of 40 psi and low wind conditions. Under normal conditions this would be selected as the recommended layout. However when high wind conditions occur, this efficiency drops to 49.05 percent. But if simultaneously with the increase in wind velocity, an increase in operating pressure is induced, the resulting efficiency will be 52.78- or an increase of 3.73 percent in absolute efficiency could be achieved by such a pressure increase.

Table 9. Average application rates in millimeters per hour for different spacings under different wind and pressure conditions.

Layout	Spacings meter	Wind	20 psi	40 psi	60 psi
Rectangular	14x16	Low	4.08	6.20	7.22
		High	3.65	5.12	7.15
Rectangular	14x14	Low	4.66	6.13	8.27
		High	4.22	5.87	8.05
Rectangular	12x14	Low	5.44	7.20	9.55
		High	4.89	6.82	9.40
Rectangular	10x14	Low	6.48	8.68	11.50
		High	5.89	7.62	11.33
Rectangular	12x12	Low	6.35	8.55	11.19
		High	5.73	7.98	11.02
Rectangular	10x12	Low	7.62	8.50	13.32
		High	6.87	8.30	13.27
Rectangular	10x10	Low	9.12	12.34	16.10
		High	8.25	11.51	15.46
Rectangular	8x10	Low	11.42	14.60	20.08
		High	10.30	14.32	19.82
Rectangular	8x8	Low	13.76	19.28	25.17
		High	12.89	17.50	25.14
Rectangular	6x8	Low	18.98	25.40	34.24
		High	17.19	23.88	33.07
Rectangular	6x6	Low	25.05	34.24	45.26
		High	22.94	28.50	47.04
Rectangular	4x6	Low	37.75	51.45	65.72
		High	34.38	47.48	66.29
Rectangular	4x4	Low	57.10	76.86	98.16
		High	51.58	76.16	98.71
Triangular	12x14	Low	5.42	---	9.66
		High	4.9	---	9.47
Triangular	12x12	Low	6.36	---	10.83
		High	5.73	---	10.93
Triangular	10x12	Low	6.94	---	12.58
		High	6.68	---	13.52

Table 10. Maximum and minimum application rates in millimeters per hour for various sprinkler layouts under different pressure and wind conditions.

Layout	Spacings meter	Wind	20 psi	40 psi	60 psi
Rectangular	14x16	Low	1.47-5.86	4.42-7.22	5.84-9.69
		High	0.48-8.98	2.96-10.17	3.09-15.11
Rectangular	14x14	Low	1.90-7.06	5.11-7.65	6.93-10.74
		High	0.48-9.22	3.10-10.17	4.50-15.11
Rectangular	12x14	Low	1.64-8.65	3.85-8.76	6.97-12.03
		High	1.25-9.88	3.66-11.39	5.21-15.63
Rectangular	10x14	Low	4.13-10.55	7.65-10.39	10.00-13.00
		High	1.88-10.98	5.52-10.37	7.41-16.15
Rectangular	12x12	Low	2.85-11.00	7.42-9.66	9.51-14.18
		High	1.68-10.72	3.99-11.53	7.10-17.31
Rectangular	10x12	Low	4.64-11.90	8.61-11.35	10.74-15.49
		High	3.94-12.18	5.79-12.76	8.03-17.84
Rectangular	10x10	Low	6.11-12.96	10.40-13.71	12.25-19.18
		High	4.85-14.58	8.61-14.05	9.35-21.29
Rectangular	8x10	Low	8.26-14.67	12.00-16.66	17.29-22.91
		High	7.25-14.39	12.05-16.41	15.68-25.47
Rectangular	8x8	Low	10.12-17.13	18.21-20.32	23.22-25.90
		High	11.10-15.77	12.92-19.23	20.93-30.72
Rectangular	6x8	Low	15.60-20.94	22.46-25.89	32.39-35.04
		High	14.23-19.78	22.22-24.56	24.57-38.40
Rectangular	6x6	Low	19.75-29.77	33.24-36.02	42.87-47.79
		High	21.99-25.03	23.67-30.65	38.78-51.07
Rectangular	4x6	Low	33.84-44.35	49.05-53.45	63.90-69.77
		High	33.51-35.24	44.88-48.93	61.54-71.16
Rectangular	4x4	Low	53.68-58.62	75.32-78.99	97.60-98.78
		High	48.80-53.71	73.63-78.30	95.12-104.01
Triangular	12x14	Low	2.63-7.67	---	7.54-11.57
		High	0.07-9.87	---	6.53-15.71
Triangular	12x12	Low	3.23-10.02	---	8.01-12.0
		High	2.69-10.23	---	7.50-16.71
Triangular	10x12	Low	5.25-11.43	---	10.10-14.0
		High	4.75-12.53	---	9.42-18.09

Further inspection of Table 7, reveals that under a rectangular layout of 12x14 meter and 40 psi on overall efficiency of 64.10 percent could be achieved when low winds occur. However, if the pressure could be increased to 60 psi this efficiency would become 52.30 percent. In fact, all efficiencies are higher under high pressure and high wind conditions than they would be under lower pressure and the same high winds. However only with layouts of 12x12 and 12x14 meters both rectangular and triangular, is the efficiency higher under 40 than under 60 psi. These, therefore, present a possible use of increased pressure to reduce the undesirable effects of wind.

Hence, based on the results of this, study, and under its given and assumed conditions it seems possible to effect a slight reduction in the undesirable effects of high winds usually occurring in the Bekaa Plain by increasing the operating pressure of sprinklers simultaneously with the advent of these high winds. This beneficial effect however, is limited to two spacings and is rather of small magnitude. Nevertheless it does denote a possibility which could yield beneficial results if it could be shown that the resulting higher efficiency effects savings compared to its increased power requirements. This will be discussed in the next section.

Evaluation of Increasing Operating Pressure

The purpose of this section is to analyse the cost of increasing the operating pressure of a sprinkler head from 40 to 60 psi during periods of high winds and to compare this cost to the savings resulting from the higher overall efficiency induced by the increased pressure. Such analysis will first be carried out for a specific spacing under given or assumed conditions. Then an attempt will be made to evaluate the problem for a general point of view.

Utilizing investment and cost data collected by Nadjafi (28) the following assumptions are made for the specific case to be analysed:

1. High winds occur daily for a period of 5 hours during the time of operation of the sprinklers.

2. The field is a 5 hectare rectangular plot with a main running off the center of its length and two laterals with 7 sprinklers each and one with 6 operating at any one instant. Both sprinklers and laterals are spaced at 12 meters.

3. The discharge of the sprinklers is 1878 and 2306 liters per hour under 40 and 60 psi respectively and the actual rate of application is this discharge multiplied by the overall efficiency of the particular layout.

4. Crop season is 180 days.

Since water application rates under 60 are higher than under 40 psi, it follows that the time of operation required to apply equal depths of irrigation water will be shorter under the higher pressure.

Furthermore the overall efficiency is higher also. Under 40 psi the overall efficiency was determined as 49.05 percent and therefore the rate of application will be

$$1878 \times 49.05 \div 144 = 6.40 \text{ mm per hour.}$$

Under 60 psi, the efficiency is 52.78 percent and the rate of water application will be

$$2306 \times 52.78 \div 144 = 8.45 \text{ mm per hour.}$$

Assuming the system will operate for 5 hours under 40 psi, it will then have to operate for only $\frac{6.40}{8.45} \times 5$ or 3.8 hours under 60 psi. Therefore the evaluation, for this specific layout is to determine the relative cost of operating 5 hours at 40 psi and 3.8 hours at 60 psi. The points of consideration are size of pump and engine, fuel consumption and water economy.

Pump and Engine

Assuming the same sizes of aluminum pipe for main and laterals- are to be used under both pressures, the total head requirement for the 40 psi operation is found to be 114 feet, while that for the 60 psi is 182. Assuming an overall pumping efficiency of 70 percent, the power requirement for 40 psi is found to be 8.5 HP unit, while for 60 psi a 16.5 HP unit is required. The cost of these units is found to be LL 2800 and LL 4100 respectively (28). Using a useful life of 15 years and an interest rate of 5 percent, the capital recovery factor is 0.0963. Thus the annual depreciation plus the expected return on the investment will be

$$2800 \times 0.0963 + 2800/2 \times 5\% = \text{LL } 340 \text{ per year for 40 psi. and}$$

$$4100 \times 0.0963 + 4100/2 \times 5\% = \text{LL } 497 \text{ per year for 60 psi.}$$

Fuel

The cost of fuel is proportional to the size of the engine and the hours of operation. Assuming both engines have the same efficiency and a conversion factor of 14.75 HP- hour per gallon (18) and fuel costs at LL 0.0118 per liter, then the relative costs will be

$(180 \times 5 \times 8.5 \div 14.75)\ 3.78 \times 0.118$ = LL 231 per season of 180 days for the 40 psi unit, and

$(180 \times 3.8 \times 16.5 \div 14.75)\ 3.78 \times 0.118$ = LL 343 per season of 180 days for the 60 psi unit.

Water

The volume of water used is proportional to the hours of operation and is equal to

$180 \times 5 \times 20 \times 1878 = 33800\ m^3$ per season under 40 psi, and

$180 \times 3.8 \times 20 \times 2306 = 31400\ m^3$ per season under 60 psi.

The cost of irrigation water is one of the difficult factors to evaluate because of the lack of satisfactory economic studies related to irrigation waters in Lebanon. Estimates vary depending on the basis of comparison. Nadjafi (28) calculated it at 2 piasters per m^3 when considering the cost of pumping as the cost of water. Using this figure then the cost of water would be

33800×0.02 = LL 676 for a season's operation under 40 psi, and

31400×0.02 = LL 628 for a season's operation under 60 psi.

Considering all cost factors together, it is apparent that the savings effected in water in no way make up for the added expenses of the larger pumping unit and increase in fuel consumption. In fact, changing to 60 psi would induce a loss of

(497 + 343 + 628) - (340 + 231 + 676) = LL 221 per season.

Thus, for this specific case, an improvement from 52.78 to 49.05 percent or 3.73 in overall efficiency would require an added expenditure of LL 221. Given these conditions the efficiency would have to be raised at least 20 percent before operation under the higher pressure would become profitable. Such an improvement was not observed in any of the layouts tested. It is therefore safe to conclude that under the conditions of this test it is not worthwhile increasing the operating pressure with the advent of strong winds. Whether it would be generally economical to increase the operating pressure of a sprinkler system to reduce the losses caused by strong varying winds cannot be answered. The factors influencing each specific situation would have to be analysed separately. Basically these factors are the intensity and duration of the winds, price level of sprinkler equipment, labor and water, crop irrigation requirements and system design. It would have been desirable to obtain a generalized relation, considering all these factors for the Bekaa Plain conditions at least, but the task proved to be too involved to be solved within the scope of this study.

Thus, it may be concluded that although variations in the operating pressure of an irrigation sprinkler system might induce improvements in the overall efficiency of the system the cost of such pressure variation is not justified.

SUMMARY AND CONCLUSION

The purpose of this study was to determine whether the undesirable effects of strong varying winds on the performance of a sprinkler system could be reduced by variations in the operating pressure of the system. To achieve this a sprinkler head was tested under varying wind and pressure conditions. A field set-up was used whereby the actual distribution of the water coming from a sprinkler head was measured by catch cans placed around the sprinkler. The sprinkler head was operated under a given pressure for periods of three hours, while the wind velocity was measured. The water collected at each can was measured and the distribution curves for each test drawn. From the 40 tests actually carried out 16 typical distribution patterns were selected and generalized patterns were obtained by averaging the patterns falling within assumed limits of pressure and wind conditions. The pressure zones were 20 and 60 psi, while the wind conditions were low and high winds. Low winds denoted periods with average speed less than 4 kilometers per hour and a range between 0 and 8 kilometers per hour, and high winds were periods with an average exceeding 20 kilometers per hour. Data on distribution under 40 psi pressure and both wind conditions were obtained from a previous study by Mutayreh (26). Based on the six generalized patterns of distribution, application rates resulting from various layouts of irrigation systems- spacings between sprinklers and laterals- were determined. A geometric summation technique was employed whereby the pattern of distribution of one head was superimposed on a layout plan, and the accumulated application at any one spot was determined.

A special field test was run to evaluate this technique. The actual application rates of three sprinklers placed on one lateral at a fixed spacing was determined in the field under varying pressure and wind conditions. This was compared to the calculated application rates and found to be in general about 10 percent higher. Thus calculated efficiencies would be actually about 10 percent lower than the true field ones. Having obtained the distribution patterns, both the uniformity coefficient and application efficiency were determined for each layout. These two were multiplied together to get the overall efficiency which was used as a measure of the layout. However, layouts applying water at a rate higher than the infiltration capacity of the soil were not considered for any further evaluation as they would not be practical to use.

A study of the overall efficiencies of the various layouts demonstrated that it would be possible to improve this efficiency for two layouts while operating under high winds by increasing the pressure. That is, it was found possible to improve the efficiency of a 40 psi system with a layout of 12x12 or 12x14 meters- either rectangular or triangular- by increasing the operating pressure to 60 psi when the wind conditions changed from low to high. The improvement, however, was not great, and ranged from 3 to 6 percent. An evaluation of this improvement consisted of determining the cost of the larger pump and engine required for developing the increased pressure, the fuel consumption and the cost of water used under both alternatives.

The analysis of specific sprinkler irrigation system under assumed field conditions revealed that the cost of the increased power was higher than the saving in water resulting from the improved efficiency. Furthermore, the cost of running the larger engine was higher than that of smaller one, although the hours of operation were shorter. Based on this study it seemed reasonable to recommend against pressure variations as a means of reducing the undesirable effects of wind. An improvement of at least 20 percent in the overall efficiency would have to be obtained before such pressure variations would be recommended. Under the conditions of this experiment, this is not possible. Whether there will ever be any situation under which this change would be recommended would require a generalized relation between various factors involved. This should indicate the effect of wind and pressure on the distribution pattern from a sprinkler head, an established probability pattern of the intensity and duration of winds, prices of sprinkler equipment, labor and water charges, crops planted and systems utilized. Such an elaborate generalization falls beyond the scope of this work.

LITERATURE CITED

1. Abd-El-Sami, A.G. The efficiency of sprinkler irrigation in Desert Soil Reclamation at Inchas Farm. Fourth Congress on Irrigation and Drainage. Trans. 4, 521, Madrid, 1960.

2. Anonymous. Sprinkling and watering machines. Division of scientific and technical information of the all-union research institute of hydro-technics and amelioration, U.S.S.R. Fourth Congress on Irrigation and Drainage. Trans. 4, 155, Madrid, 1960.

3. Ayers, H.D. The economics of portable sprinkler irrigation system design for annual crops in subhumid areas. Fourth Congress on Irrigation and Drainage. Trans. 4, 21, Madrid, 1960.

4. Bagely, J.M., and V.E. Hansen. Sprinkler irrigation. Utah. Agr. Exp. Farm and Home Science. 17, 30, 1956.

5. Bauzil, V. Traite d'Irrigation. Eiyrolles, Paris, 1952.

6. Benami, A., and F.R. Hore. A new irrigation sprinkler distribution coefficient. Agr. Eng. Trans. 7, 157, 1964.

7. Bonnal, C. Manual of Collective Sprinkler Irrigation. Organisation for economic cooperation and development. Paris, 1963.

8. Carreker, J.R. Results of irrigation research in Georgia. Agr. Eng. 22, 243, 1948.

9. Criddle, W.D., D. Sterling, C.H. Pair, and D.G. Schockley. Methods for Evaluating Irrigation Systems. Agriculture Handbook, No. 82. Soil Conservation Service. U.S.D.A., 1956.

10. Duffee, F.W. Low pressure sprinkler irrigation. Agr. Eng. 13, 97, 1939.

11. Frost, K.R., and H.C. Schwalen. Sprinkler evaporation losses. Agr. Eng. 36, 526, 1962.

12. Fuhriman, D.K. Sprinkler irrigation. Utah. Agr. Exp. Farm and Home Science. 15, 32, 1954.

13. Gray, A.S. Sprinkler Irrigation Handbook. RainBird Sprinkler Manufacturing Corporation. California, 1951.

14. Gray, A.S. Sprinkler Irrigation Handbook. RainBird Sprinkler Manufacturing Corporation. California, 1961.

15. Hamilton, F.B. and J.F. Shrunk. Sprinkler versus gravity irrigation, a basis for choice of the best system. Agr. Eng. 34, 246, 1953.

16. Houk, I.E. Irrigation Engineering. Vol. 1. John Wiley and Sons, Inc., New York, 1957.

17. Houk, I.E. Irrigation Engineering. Vol. 2. John Wiley and Sons, Inc., New York, 1957.

18. Israelsen, O.W., and V.E. Hansen. Irrigation Principles and Practices. John Wiley and Sons, Inc., New York, 1962.

19. Kovern, H.C. The effect of wind on the uniformity of water distribution by some rotary sprinklers. Sci. Agr. 32, 226, 1962.

20. Krude, E.G., P.E. Schlensenuer, W.E. Selby, and B.R. Somerhalder. Sprinkler and furrow irrigation efficiencies. Agr. Eng. 43, 636, 1962.

21. Lewis, M.R. Practical Irrigation. Farmer's Bulletin, No. 1922, 143.

22. Lozano, F.G. Influence of the design of a sprinkler irrigation installation on its efficiency and the cost of handling. Fourth Congress on Irrigation and Drainage. Trans. 4, 289, Madrid, 1962.

23. McCulloch, A.W. Design procedure for portable sprinkler irrigation. Agr. Eng. 30, 23, 1949.

24. Molenaar, A., J.C., Unbewust, M.W. Hoisven, and M.C. Jensen. Factors affecting distribution of water from rotating sprinklers. Washington. Agr. Exp. Sta. Circ. 284, 1954.

25. Molenaar, A. Irrigation by Sprinkling. F.A.O. Agriculture Development Paper, No. 65, Rome, 1960.

26. Mutayreh, I.U. Effect of wind speed on the performance of sprinkler in the Bekaa Plain. M.S. Thesis. American University of Beirut. Beirut, Lebanon, 1964.

27. Myes, L.E., and H.R. Haise. Water application efficiency of surface and sprinkler methods of irrigation. Fourth Congress on Irrigation Methods and Drainage. Trans. 4, 10, Madrid, 1960.

28. Nadjafi, A. The effect of wind on the cost of irrigation by sprinklers. M.S. Thesis. American University of Beirut. Beirut, Lebanon, 1963.

29. Piekert, F.W. Irrigation with sprinklers and portable pipes. Agr. Eng. 29, 541, 1948.

30. Powers, W.T. Irrigation efficiency studies. Soil Sci. Soc. Amer. Proc. 4, 415, 1939.

31. Quackenbush, H.T., and D.G. Shockley. The use of sprinklers for irrigation. U.S.D.A. Water Yearbook, 267, 1955.

32. Schwab, G.O., and R.K. Frevert. Elementary Water and Soil Engineering. John Wiley and Sons, Inc., New York, 1957.

33. Scott, V.H. Sprinkler irrigation. California. Agr. Exp. Sta. Circ. 456, 1956.

34. Selim, M.A., and F. Nicola. Sprinkler irrigation and comparison with other methods in Egypt. Fourth Congress on Irrigation and Drainage. Trans. 4, 167, Madrid, 1960.

35. Strong, D.C. Economic evaluation of alternative facilities for surface and sprinkler irrigation in Utah. Agr. Exp. Sta. Logan. 1962.

36. Thorne, D.W., and H.B. Peterson. Irrigated Soils. Blakston Co., Inc., New York, 1954.

37. Uner, N. Irrigation efficiencies. Regional Irrigation Practices Leadership. International Cooperation Administration, Ismir, 1959.

38. Wane, C.D. Irrigation. Agricultural Engineer's Handbook. McGraw Hill Book Co., Inc., New York, 1961.

39. Wilcox, J.C., and G.E. Swalen. Uniformity of water distribution by some undertree orchard sprinkler. Sci. Agr. 27, 565, 1947.

40. Woodward, G.O. (Editor). Sprinkler Irrigation. Sprinkler Association, Washington, 1959.