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EVALUATION OF WATER APPLICATION OF A CENTER-PIVOT SPRINKLER IRRIGATION SYSTEM

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IN THE NAME OF ALMIGHTY GOD,

THE MAGNIFICANT, THE MERCIFUL

ABSTRACT

Uniformity of water application and application rates of a center-pivot irrigation system were measured. Coefficients of uniformity were calculated for different can spacings and different number of rows.

To this end a basic setup of three radial rows of cans with an angle of 3° between adjacent rows was used. Cans were spaced 5 m apart in each row.

Application rates of the system were also measured with cans at different strategic locations along the lateral and compared with the infiltration rate of the soil which was measured by a double concentric ring infiltrometer.

Average coefficient of uniformity of the system was found to be 80 percent. Cans spacings of 10 m and 5 m were found to be equally good for the evaluation of the system, while 15-m spacing gave less accurate results. The inclusion of end can observations had a significant effect on the coefficient of uniformity.

Spinner arms were found to affect the uniformity of water application adversely. It was suggested that the use of some special type of nozzle at the ends of the spinner arms might reduce the effect.

The application rates of the system were much less than the infiltration rate of soil, and as a result, no potential for runoff was found.

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CHAPTER I

INTRODUCTION

Water is one of the basic necessities of plants. In areas where the consumptive use of crops exceeds natural precipitation, supplemental irrigation is essential to replenish the soil moisture deficit for successful crop production. Irrigation is an old practice, which has been used in the Indus Valley since 5000 B.C. (Khan 1973). Basin irrigation introduced in the Nile Valley around 3000 B.C. still plays an important role in Egyptian agriculture (Henry 1971).

The total world area under irrigation at present is estimated to be of the order of over 230 million hectares (FAO 1977). About 70 percent of this irrigated area lies in Asia alone. Irrigation must be increased and improved worldwide as one of the ways of meeting the increasing food and fibre needs of the rapidly growing population. But at present, the world's irrigated area is being increased at the rate of only one percent annually, which some people believe is unsatisfactory. One of the reasons for such a low growth rate is the lack of suitable sources of irrigation water.

Water is a scarce resource. To obtain maximum benefits from this natural resource, its optimal use is essential. Surface and sprinkler irrigation are the most common

irrigation methods and the choice depends mainly on the source of water supply, topography and characteristics of soil, and economic and social conditions.

Surface irrigation systems, if properly designed, give good results in suitable conditions. A poorly designed system leads to high water losses creating waterlogging and salinity problems and a drainage requirement and it often does not apply water as and when required by the crop (Alvi 1978).

Sprinkler irrigation methods have some advantages over surface irrigation (Korven and Randall 1975), such as

i) sprinkler irrigation can be used on lands which are difficult or impossible to irrigate by surface methods,

ii) sprinkler irrigation is suitable for light application, and

iii) sprinkler irrigation results in better uniformity of application and high application efficiency.

There is a tendency towards the automation of irrigation systems in some countries due to high cost and scarcity of agriculture labour. This is why center-pivot sprinkler irrigation is becoming more and more popular. The system's ability to irrigate rolling terrain with a wide range of application depths adds to its versatility. The center-pivot system has proven to be very useful for light applications, which can be beneficial in promoting seed germination and in preventing wind erosion of soil. However, the present

energy crisis may affect the poularity of this sytem, as it is a high consumer of energy per unit volume of water applied (Hoffman et al. 1974).

The center-pivot system consists of a pipeline supported on towers usually spaced about 61 m apart. The length of the lateral pipeline varies from approximately 200 m to 800 m but 400 m is the most common length (Splinter 1976). Water is introduced at the pivot and flows outward through the pipeline, supplying each of the individual sprinkler heads. Center-pivot systems vary a great deal in their design. Some systems use only one type of sprinkler heads and vary the spacings between the sprinkler heads on the lateral to obtain desirable application patterns, while others use constant spacings and vary the size of the nozzles. Combining the two principles results in other designs, in which both the spacings between the sprinkler heads and size of the nozzles are varied.

This system is ideal to irrigate a circular area. But, since the fields are usually square or rectangular in shape, only about 75 percent of the area of a typical quarter-section is effectively irrigated by the basic unit. With an endgun, an additional five percent of the total area can be irrigated, but 20 percent of the area is still left to irrigate. This not only reduces the area under main crop, but also increases initial cost per unit area of the irrigated land. This problem can be overcome, to a large extent, by the addition of a 'corner-pivot' system to the conventional

center-pivot machine. The center-pivot assembly pivots about the outer tower and applies water at the corners of the field. This increases the irrigated area to approximately 96 percent and reduces the investment per unit irrigated area appreciably (Callies 1978).

As the perimeter of a circle is proportional to the radial distance and the sprinkler heads at different distances from the pivot point travel at different speeds, the time during which water is applied to a point is also different along the lateral. To compensate for this and to achieve a reasonably uniform depth of water, the application rate is low near the pivot and increases toward the end tower. This may cause undesirable runoff near the endgun on soils of low water intake rate.

In Manitoba, center-pivot sprinkler irrigation is becoming popular among the farmers in some areas for the irrigation of high-valued crops. In Alberta, this system was first introduced in 1961 and now it is a popular sprinkler irrigation method in that province (Ring and Heermann 1978). In the USA, the number of center-pivot irrigation systems is increasing rapidly and a lot of research work has been done and is in progress. Most of the research results are transferable and applicable to other places. There are, however, many problems which need either further investigations, or which must be studied in the specific local environmental conditions.

The objectives of the research reported in this thesis

were as follows:

i) to measure the uniformity of application of a self-propelled center-pivot sprinkler irrigation system.

ii) to determine the rate and the depth of application of the system.

iii) to determine the water application losses and the wind effect.

iv) to measure the intake characteristics of the soil.

v) to evaluate the potential for runoff under the center-pivot irrigation system.

CHAPTER II

REVIEW OF LITERATURE

Considerable amount of literature has been written on several aspects of center-pivot sprinkler irrigation since its introduction in 1952. The variables reviewed for this study were depth and uniformity of application, application rate and runoff, infiltration rate of the soil, and application losses due to evaporation and drifting.

2.1 Depth and Uniformity of Application

Christiansen's coefficient of uniformity is generally used to measure the uniformity of application in sprinkler irrigation (Pair et al. 1975). The formula used to calculate the coefficient (Christiansen 1942) is:

$$Cu = 100(1.0 - \frac{\Sigma |x|}{MN}) \qquad 2.1$$

where: Cu = Christiansen uniformity coefficient

x = deviation of an individual observation from the mean

M = mean of all observations

N = number of observations.

An absolutely uniform application is represented by a coefficient of 100 percent and a less uniform application by some lower percentage. The higher the coefficient of uniformity, the better the water application of the system.

Usually, a system is considered satisfactory if it has a coefficient of uniformity higher than 70 percent.

In equation 2.1, it is assumed that each catch can represents an equal sample area. This is the case in sprinkler systems other than center pivots. For cans set out radially from the pivot point, this would only be true if the can spacings varied inversely with the distance from the pivot. Heermann and Hein (1968) suggested a method of calculating the coefficient of uniformity for the center-pivot system for radially located cans. They determined the sample area represented by each can and then by considering the volume of water applied to this area rather than the depth applied at a point, a formula very similar to equation 2.1 was used to calculate the coefficient. If the distance between the pivot and first can is one-half of the distance between the succeeding cans, then the relationship proposed by Heermann and Hein reduces to the following (Ring and Heermann 1978):

$$Cu = 100\left(1.0 - \frac{\Sigma R_S |D_S - D|}{D \Sigma R_S}\right) \qquad 2.2$$

where: Cu = weighted Christiansen coefficient of uniformity,

D_S = depth at any point

D = Weighted mean depth, given as

$D = \Sigma R_S D_S / \Sigma R_S$

R_S = weighting factor equal to the distance from the pivot, given as

$R_S = 0.5S + (i-1)S$ where:

i = subscript referring to the ith can from the pivot

S = spacing between cans.

Heermann and Hein (1968) used a relationship quite similar to equation 2.2 to calculate the coefficient of uniformity for a center-pivot system. The measured coefficient of uniformity was reported as 81.3 percent and 89.4 percent with and without an endgun, respectively.

Pair (1968) compared the performance of five different sprinkler irrigation systems including the center pivot. Cans were placed in rectangular grid patterns for each system to collect the spray. Each system tested had a coefficient of uniformity above the acceptable level. The average coefficient of uniformity for the center-pivot system was 84 percent at an average wind speed of 9.5 $km.h^{-1}$. The uniformity coefficient for the center-pivot system was calculated by using equation 2.1 since the cans were not set out radially.

Hall (1974), like Pair (1968), used cans placed in rectangular grid patterns to measure the coefficient of uniformity of center-pivot systems. Rectangular areas of 3.05 m wide were marked out between adjacent towers. Two rows of cans were set out along the sides of the rectangles and one in the middle of each rectangle, offset from the other two rows. For succeeding towers the rectangles were offset from the previous ones and as a result, the unit passed over different grids at different times.

Jones (1974) used radially located cans to evaluate the performance of a center-pivot system. Cans were spaced 6.1 m apart in a single line extending radially from the pivot. No correction factor for evaporation from the cans was applied. The average coefficient of uniformity as found in his experiment was 85.2 percent at wind speeds ranging from 4.5 to 22.4 $km.h^{-1}$.

Ring (1975) measured the coefficient of uniformity of five center-pivot irrigation systems by using cans. Kerosene oil was used to suppress evaporation from the surface of the cans. The results obtained in his study are shown in table 2.1. These results indicate that an electric-motor-driven system had the highest average uniformity coefficient (89.6 percent) and the spinner-arm-driven unit had the lowest coefficient of uniformity (70 percent) among the systems tested.

Petersen (1976) studied the performance of different sprinkler heads used with center-pivot irrigation systems. The sprinklers were placed on the top of a 3.1 m tall stationary riser. Different operating pressures were used in steps from 200 kPa to 550 kPa for each head tested. He reported that part-circle sprinklers and spray nozzles had uniformities comparable to the full-circle sprinklers, but the former had higher application rates than full-circle sprinkler heads.

At present, a large portion of a farm's energy is used to operate a high-pressure center-pivot irrigation system, which usually ranges from 414 kPa to 552 kPa depending upon

TABLE 2.1 RESULTS OF CENTER-PIVOT EVALUATION IN ALBERTA (Ring 1975)

System Number	Test No.	Test Time	Wind Speed Min-Ave-Max $km.h^{-1}$	Temperature °C	Relative Humidity %	Average Application cm	Coefficient of Uniformity %
1-74[1]	74-001	16:00	*	21	32	1.56	83
1-74	74-002	01:00	*	13	55	1.93	89
1-74	74-004	18:00	*	28	29	1.73	88
1-74	74-005	02:00	*	14	69	2.02	91
1-74	74-006	10:30	*	22	48	1.75	90
1-74	74-007	19:00	8 - 19 - 34	30	20	1.65	90
1-74	74-008	04:00	0 - 11 - 24	13	60	1.73	89
1-74	74-009	13:00	5 - 14 - 29	22	52	1.68	91
1-74	74-010	09:00	2 - 13 - 26	20	67	1.85	89
1-74	74-011	19:30	0 - 8 - 18	25	36	2.18	91
1-74	74-012	06:00	0 - 6 - 11	14	76	1.98	87
1-74	74-013	16:30	0 - 6 - 21	30	31	2.08	91
1-74	74-014	03:00	2 - 8 - 19	12	72	2.39	91
2-74[2]	74-015	21:00	2 - 10 - 19	15	60	2.41	79
2-74	74-016	18:00	5 - 18 - 26	20	35	2.26	82

TABLE 2.1 (Continued)

System Number	Test No.	Test Time	Wind Speed Min-Ave-Max $km.h^{-1}$	Temperature °C	Relative Humidity %	Average Application cm	Coefficient of Uniformity %
2-74	74-017	15:00	2 - 10 - 23	17	51	2.69	78
2-74	74-018	13:00	0 - 8 - *	*	*	2.41	81
2-74	74-019	18:00	10 - 26 - 48	22	33	2.13	71
2-74	74-020	16:00	0 - 10 - 23	22	33	2.34	79
3-74[2]	74-021	18:00	13 - 26 - 41	28	26	1.60	89
4-74[1]	74-022	21:00	0 - 2 - 6	12	57	2.46	89
2-74[2]	74-023	01:00	0 - 8 - 19	*	*	2.57	76
2-74	74-024	24:00	* 8 - *	*	*	2.67	70
2-74	74-025	22:00	0 - 8 - 26	*	*	2.54	77
2-74	74-026	18:00	0 - 3 - 10	*	*	3.20	83
2-74	74-028	04:00	0 - 2 - 8	11	69	2.92	75
2-74	74-029	19:30	0 - 5 - 16	20	55	2.67	78
2-74	74-030	18:00	0 - 8 - 23	24	23	2.87	81
2-74	74-031	17:00	0 - 3 - 10	27	20	3.12	76
5-74[3]	74-032	03:00	*	*	*	4.24	70

* Data not available due to equipment not installed or malfunction.

1. Electric motor. 2. Water cylinder. 3. Spinner-arm.

the length of the lateral. If the operating pressure can be reduced without significantly affecting the system's ability to distribute water uniformly, much of the farm energy could be saved. Ali and Barefoot (1978), and Barefoot (1978) simulated the performance of a center-pivot irrigation system at reduced pressure, using Petersen's (1976) method for collecting data. Stationary sprinkler patterns were obtained for different sprinkler heads at various trajectory angles, from a 2.7 m tall stationary riser operating at 134, 278, 415 and 556 kPa. The wetted diameter for all types of head increased as the operating pressure was increased from 134 to 278 kPa. They reported that pressure higher than 278 kPa was not very effective in increasing the wetted diameter or the coefficient of uniformity, when the recommended spacing was used. Comparison of different sprinkler heads showed that part-circle sprinkler and spray nozzles had 1.7 and 5.5 times higher average application rates respectively than full-circle sprinklers at a spacing of 10 m and a flow rate of about 44 $L.min^{-1}$.

Kelso and Jarrett (1978) developed a computer model for the design of a center-pivot sprinkler irrigation system. Three basic input variables used were the system flow rate, length of the system and the sprinkler spacing. The flow rate of the system was assumed such as to meet the consumptive use of the crop. Sprinkler sizes were calculated by assuming a constant depth and spacing between the sprinkler heads. The model had the flexibility to operate with or

without an endgun. The predicted coefficient of uniformity was about 92 percent and 95 percent with and without an endgun, respectively.

The design of a center-pivot system is usually based on the assumption either of an elliptical or of a triangular pattern for individual sprinklers. Morgan (1978) presented the hypothesis that "individual sprinkler head patterns affect center pivot machine water distribution uniformity". He suggested that by considering the actual patterns produced by the sprinkler heads, the water distribution of the center-pivot system can be improved.

Ring and Heermann (1978) compared the measured coefficient of uniformity with the theoretical ones. The results showed a good analogy, except near the pivot and at the endgun. They suggested that some standard radial distance should be used to calculate and compare the coefficients of uniformity of various systems, due to its pronounced effect on the coefficient. They recommended that two radial rows of cans, with a can spacing of 5 or 10 m should be used for better measurement of the coefficient of uniformity of center-pivot systems.

2.2 Application Rate and Runoff

It is generally assumed that commonly used irrigation sprinklers have triangular or elliptical stationary distribution patterns. The application rate is maximum at the center of the pattern and decreases with increasing radius. However, the rate decreases much more rapidly for the

triangular pattern as the distance from the sprinkler increases. Figure 2.1 illustrates the stationary sprinkler patterns for the triangular and elliptical cross sections.

When these sprinklers are used on a lateral, more uniform water application is achieved by carefully overlapping the individual patterns. A stationary sprinkler system applies water at a constant hourly rate, while the water application rate to a point varies continuously with time during application by any moving sprinkler system. As the system approaches a point, the application rate starts from zero, increases to a maximum, and then decreases to zero again as the moving unit passes over the location (Pair et al. 1975).

The average application rate of the center-pivot system is low near the pivot and increases toward the end tower. This increase in rate is essential if uniform application of water is desired because:

i) water application time is inversely proportional to the distance from the pivot

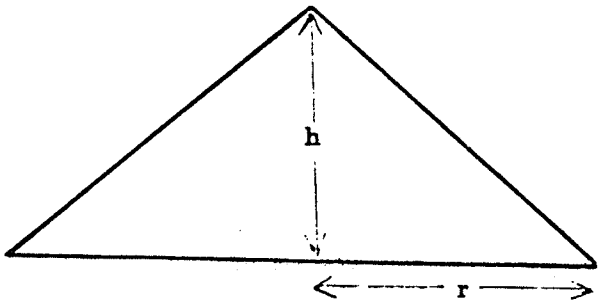
ii) irrigated area increases with square of the radial distance.

Bittinger and Longenbaugh (1962) derived mathematical relationships for moving sprinkler patterns for a circular as well as a straight-line path. They concluded that at a distance from the pivot of about five times the pattern radius (at a point where the ratio of the radial distance to the pattern radius is equal to 5), straight-line motion

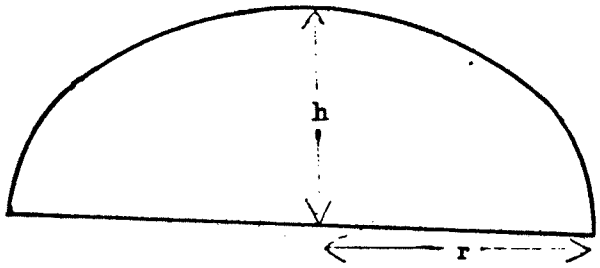
LEGEND

h = Maximum application rate

r = sprinkler pattern radius



Triangular



Elliptical

Figure 2.1 Application-rate patterns for stationary sprinklers.

could be assumed for center-pivot systems. The best distribution patterns for moving systems can be obtained at sprinkler spacings of one time and 1.4 times the pattern radii for both triangular and elliptical patterns, respectively.

Heermann and Hein (1968) used equations derived by Bittinger and Longenbaugh (1962) to simulate the application patterns of moving sprinkler systems. Measured and theoretical results showed good conformity. The coefficient of uniformity was calculated by considering the volume of water applied to a point rather than the depth. Runoff under the systems was calculated by assuming constant application rates for the systems, using an empirical water intake function. Their results showed that the percentage of the total depth of water available for runoff was approximately proportional to the distance from the pivot.

Kincaid et al. (1969) measured and estimated runoff under a center-pivot irrigation system from a soil having a time-dependent intake rate. Runoff was calculated by superimposing the intake curve of the soil, obtained from infiltrometer tests, on the application rate curves. For better estimation of potential runoff, the intake function of the soil was modified to account for the low initial application rate of the moving sprinklers. Measured and calculated results obtained from delaying the intake function, showed reasonably good agreement.

The center-pivot system is unique both in design and in method of operation. By changing the speed of the system,

any depth of water can be applied. Dillon et al. (1972) discussed the design procedure in detail. Consumptive use of the crop, intake rate of the soil and average application rates of the system are considered as the basic design criteria. The average application rates of a well designed system should not exceed the intake rate of the soil. If the peak application rate of the system is higher than the final intake rate of the soil, one can utilize the higher initial intake rate of the soil by increasing the speed of the system to reduce runoff. Runoff time was measured on three center-pivot systems near the outer tower, where runoff is generally expected. The difference between predicted and measured runoff time was in the range of 4 percent to 34 percent.

Runoff under a center-pivot irrigation system can be reduced by either different soil management or by reducing and/or changing the application patterns. Aarstad and Miller (1973) used various surface treatments to reduce runoff. Plots studied were located between the last two towers. It was reported that yield was increased by reducing runoff.

Addink et al. (1975) used a model developed by Smith and Woolhiser to predict runoff from the symmetrical and skewed patterns obtained from laboratory tests. The forward-skewed application pattern had 11 percent less runoff. They proposed the use of a new type of sprinkler head or possible settings of part-circle "van" type sprinklers with nozzles in two directions, for forward-skewed application patterns.

Chu (1977b) used an infiltration model developed by Green and Ampt to analyze the time-dependent application under center-pivot systems. The application pattern was assumed to be elliptical. Water accumulated on the surface was defined as the difference between the amount of water applied and that infiltrated. By knowing the volume of water infiltrated and various other parameters, the allowable maximum application rate for a center-pivot system was predicted.

Slack (1977) applied a modified Mein and Larson model to predict time to surface ponding. Measured instantaneous application rate curves, from two center-pivot systems, were neither triangular nor elliptical. In spite of this, a triangular pattern was assumed to predict time to, and volume of, runoff. Tests showed that the model did a good job of predicting time to runoff but did not perform so well in predicting volume of runoff.

2.3 Infiltration Rate of the Soil

Infiltration is the downward entry of water into the soil. It depends upon the physical characteristics of the soil, the condition of the soil surface and the antecedent soil moisture. In the design of an irrigation system, it is one of the basic variables that is to be satisfied.

The infiltration rate of a dry soil is high initially and decreases rapidly with time and increase of soil moisture. After some time, it approaches a constant value, termed as

the basic or final intake rate. This time-intake relationship is usually represented by the following empirical relationship:

$$I = b + at^n \qquad 2.3$$

where: I = infiltration rate of the soil

t = elapsed time or infiltration opportunity time

a, b and n are characteristic constants of the soil.

Kincaid et al. (1969) used the above relationship to predict runoff under center-pivot irrigation system. This equation gave a better estimation of runoff than the constant intake rate.

A number of studies have been conducted to describe adequately the infiltration process. Holtan (1961) described the infiltration process as a function of the remaining volume of potential storage and the permeability of the control depth by the following equation:

$$f_p = f_c + a(S_p - F)^n \qquad 2.4$$

where: f_p = infiltration capacity

S_p = storage potential of the soil above the control depth

F = accumulated infiltration

f_c = constant infiltration rate

a,n= constants obtained as the intercept and slope respectively of a log-log plot of $(f_p - f_c)$ vs $(S_p - F)$.

The difficulty in applying the Holtan (1961) equation is in defining the control depth. As observed by Smith (1976), if the values of the constants of equation 2.4 are derived from a certain situation, the infiltration will have an initial maximum rate depending on the chosen value of the control depth. This relationship does not agree with hydraulic principles.

Green and Ampt (1911) derived a relationship based on physically measured parameters, with the assumption that water was ponded on the surface. If the depth of ponding is negligible, then the resulting equation is:

$$f_p = \frac{dF}{dt} = K_s \ (1.0 + \frac{s.IMD}{F}) \qquad 2.5$$

where: K_s = saturated hydraulic conductivity

IMD = initial moisture deficit, i.e. porosity minus initial moisture content

s = capillary suction of the wetting front, equivalent to water column height.

The Green and Ampt equation or some modified form of it is considered more appropriate to describe the infiltration process since it utilizes physical parameters which can be determined experimentally. Mein and Larson (1973) developed a two-stage model which predicts infiltration volume prior to the beginning of runoff and infiltration capacity. The infiltration capacity after runoff was predicted by the Green and Ampt model while the infiltration volume prior to

runoff was described from a modified form of Darcy's law for constant application rate. The equation is:

$$F_s = \frac{s.IMD}{A/K_s - 1} \qquad 2.6$$

where: F_s = infiltration volume prior to runoff

A = constant application rate.

The assumption in the derivation of the above equation, apart from those inherent in Darcy's law, was that at the instant of surface saturation the rate of infiltration is equal to the application rate.

Chu (1977a) had shown that equation 2.6 is equally valid for the time-dependent application rates, if the application intensity is a function of time. Thus, for a time-dependent application rate, equation 2.6 may be rewritten as:

$$F_s = \frac{s.IMD}{\frac{A(t)}{K_s} - 1} \qquad 2.7$$

Addink and Miles (1973), and Chu (1977b) simulated the infiltration process for time-dependent application rates as in center-pivot systems. Chu presented the graphical solution of the equations derived for allowable maximum application rates for convenient selection of center-pivot systems for given ground surface conditions.

2.4 Sprinkler Losses

Loss of sprinkled water occurred in different ways: (1) evaporation in the air within the sprinkler pattern, (2) interception by the vegetation, and (3) drift when

sprinklers are operated under windy condition (Kraus 1966).

Christiansen (1942) used a catch can method to estimate evaporation losses. He reported losses ranging from 10 percent to 42 percent for afternoon tests. Early morning tests had average losses of four percent. No correlations were made with climatic factors, but losses were high on hot, dry days.

Frost and Schwalen (1960) used small crop tanks which were intermittently sprinkled. They concluded that spray losses were small and equal to or slightly greater than the reduction in evapotranspiration; hence, the total losses during sprinkling were about equal to evapotranspiration losses of vegetation when not sprinkled. Direct correlation of spray losses was found with vapour pressure deficit and wind speed.

In research conducted by Kraus (1966), it was found that total application losses from sprinkler systems ranged from 3.4 percent to 17 percent at wind speeds of 3.7 $km.h^{-1}$ to 16 $km.h^{-1}$. Results obtained in this research matched closely that of Frost and Schwalen (1960).

Sternberg (1967) measured sprinkler losses using catch cans and lysimeters. He reported that, for low wind speeds, spray losses ranged from 17 percent to 22 percent for day and 11 percent to 16 percent for night irrigation. Sprinkler irrigation causes a 3°C to 5°C dry-bulb temperature reduction within the sprinkled pattern which would reduce evapotranspiration during the sprinkling process.

Anderson and Brown (1972) reported that evaporation losses varied from 20 percent to 28 percent during the irrigation season for the center-pivot system tested. Evaporation loss on calm days was estimated to be from five percent to ten percent.

Jones (1974) calculated evaporation losses for a center-pivot irrigation system from the measured precipitation data. He assumed evaporation losses as the difference between the applied depth, and the depth of water collected in the rain gages. Average values of evaporation, losses were reported as 20.4 percent for day-time and 10.6 percent for night-time irrigation. Clark and Finley (1975) found that evaporation losses mainly depend upon the vapour pressure deficit and the wind speed. The nozzle size and air temperature had little effect on evaporation losses. They reported that when the average wind speed was less than 16 $km.h^{-1}$, the vapour pressure deficit had the greatest influence on evaporation loss. At wind speeds higher than 16 $km.h^{-1}$, wind was the controlling factor, and evaporation losses increased exponentially. But, Seginer and Kostrinsky (1975) reported that wind speed had little effect on evaporation losses; it only distorted the application pattern. The latter result is seriously doubted and a possible reason may be the high humidity which was associated with the high wind speed or some discrepancy in their measurements.

Petersen (1976) reported evaporation losses for different sprinkler heads. The average evaporation losses for

part-circle sprinklers, full-circle sprinklers, and spray nozzles were 17.2 percent, 25.4 percent and 2.3 percent, respectively.

2.5 Corner-pivot System

The center-pivot irrigation machine, in spite of its many advantages, has one prime disadvantage which is the inability of a normal center-pivot system to irrigate a rectangular or irregular-shaped field. This limitation of the system has been removed to a great extent by the development of the 'corner-pivot' system (Ronald 1976). This attachment is used to extend the reach of the standard machine to water the corners or irregular-shaped areas along the perimeter of a field. The corner-pivot system consists of a long-span single-tower center-pivot irrigation machine, which is attached to, and pivots about, the outermost tower of a conventional center-pivot system.

2.5.1 Method of operation

The mode of operation of the corner-pivot system is unique. The corner-pivot assembly travels around the field in a folded position such that it is nearly parallel to the main machine. In this position the corner span travels a common path with the next-to-last tower of the main machine. The operation of the corner-pivot assembly and the area irrigated by the main machine, endgun and corner-pivot assembly are illustrated in figure 2.2. At the corners of the field where the operation of the corner-pivot assembly is needed,

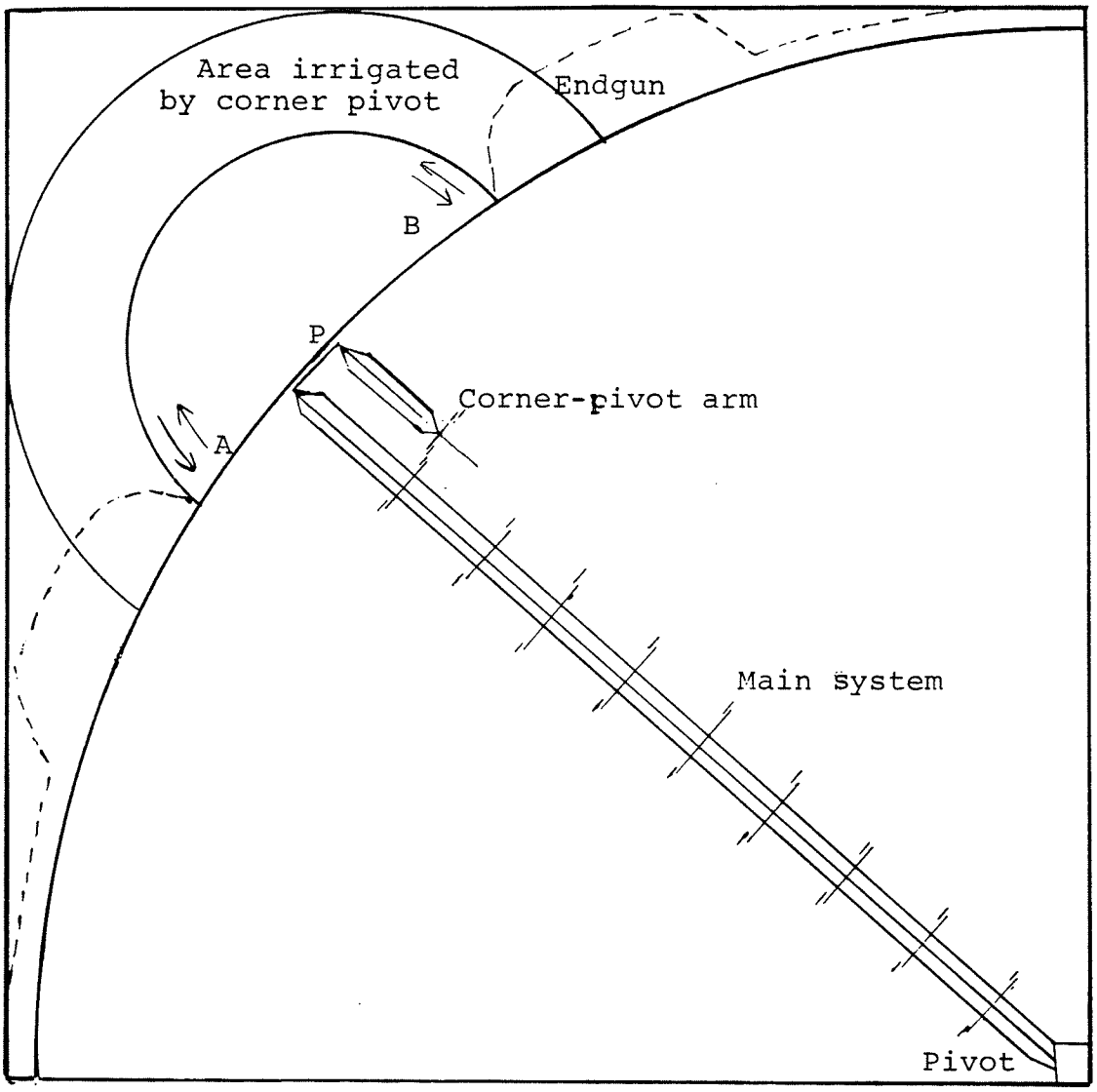


Figure 2.2 Area irrigated by the main system, corner-pivot assembly and endgun.

'a tall marker stake' which is fixed in the ground, activates the corner-pivot arm (Callies 1978). This signal stops the main machine and the corner-pivot arm swings rapidly outward to point B. It continues to apply the first 50 percent of the total corner water application to point A. As soon as it reaches point A, it reverses its direction of travel and applies the second half of the total water application on the return swing. On completion of the return swing, the corner-pivot arm swings back to its initial position and the operation of main machine starts its normal operation again.

2.6 Advantages of Center-pivot System

Many of research workers have listed some good features of the center-pivot system over other sprinkler systems which are as follows:

i) a center-pivot system is ideal for light applications to reduce soil erosion or to promote germination.

ii) economical and uniform applications of fertilizers and herbicides are obtained when applied with center-pivot systems (Fischbach 1975).

iii) the ability of a center-pivot system to irrigate rolling terrain makes it more versatile.

iv) labour requirements for this system are much lower than other irrigation systems.

v) in areas where night irrigation is practised, this system is more suitable than other sprinkler

systems (Alvi 1978).

vi) careful management of a center-pivot system can reduce the capital cost per unit land area without affecting yield materially.

CHAPTER III

EXPERIMENTAL METHODS AND INSTRUMENTATION

3.1 Location

The research reported in this thesis was conducted in the summer of 1978 on a private farm belonging to Mr. Allison Briggs from Portage la Prairie, Manitoba. The property is known in the area as "Cousin's Farm" and it is situated about 100 km west of Winnipeg and about 15 km southwest of Portage la Prairie. The legal description of the field is the eastern half of section 35, township 10, range 8 west of first principal meridian (E½ 35-10-8W1).

3.2 Tophography of the Field and Soil Characteristics

The field which has a rolling topography, was surveyed at the beginning of the 1978 growing season and a contour map of location no. 1 was prepared on the basis of a tacheometric survey (figure 3.1). The interval of the contours is 20 cm. The difference between the highest and the lowest point in the area surveyed is 1.6 m and the undulating topography of the field is also evident from figure 3.1. The top of the irrigation hydrant at the end of the underground water supply line was used as a bench mark.

The soil belongs to the Almasippi series and, as such, it shows a wide variation in texture and in the thickness of the surface layer. The texture ranges from moderately coarse

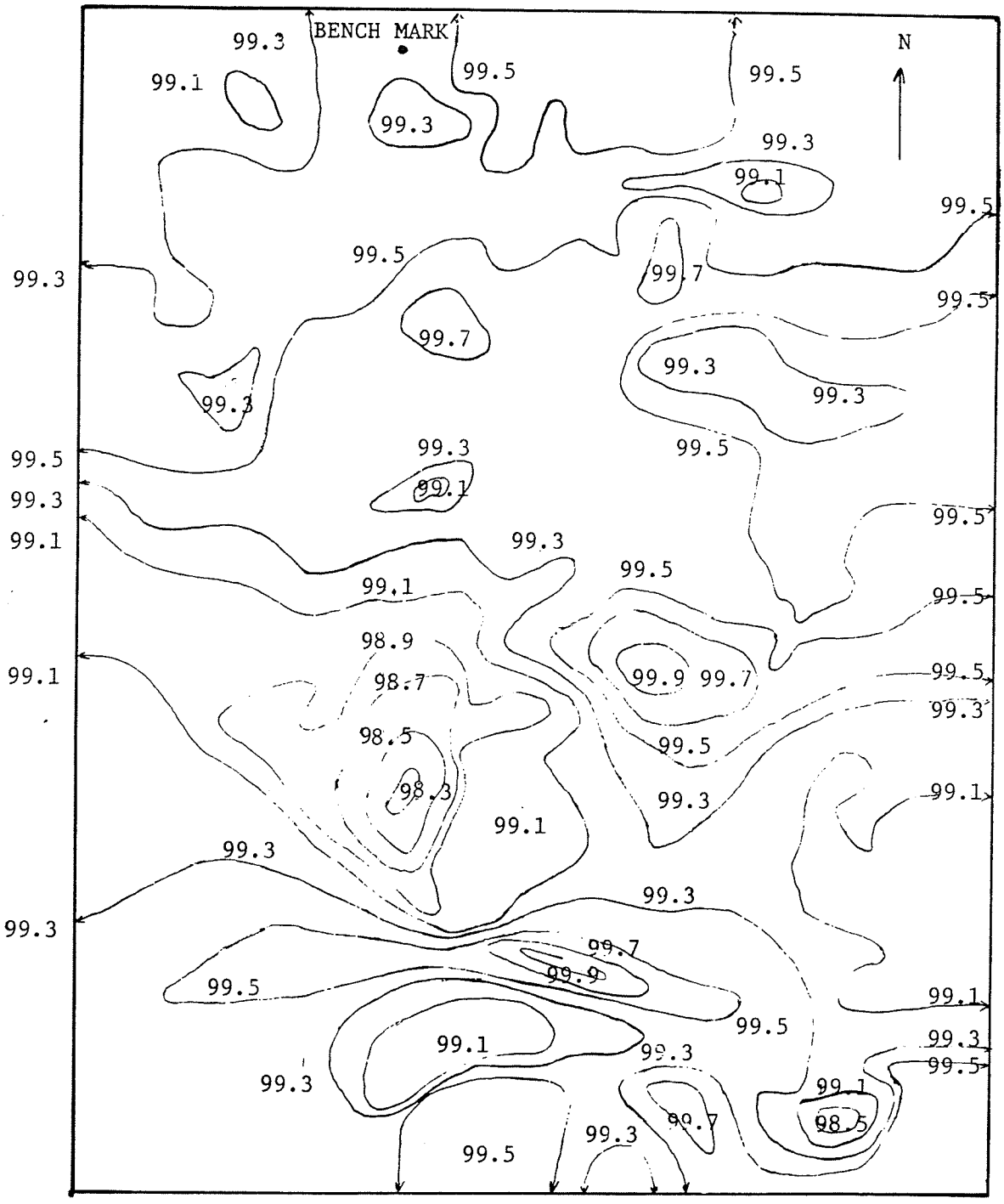


Figure 3.1 Contour map of Cousin's field (NE section 35-10-8W1)
Highest elevation 99.9 m Lowest elevation 98.3 m
Scale 1:1650

sand to very fine sand and the depth ranges from more than three m to less than one m. The layer underlying the sandy surface sediments consists of stratified silts with silty clay loam as a dominant textural class. The depth of this underlying layer is about 60 m. The water table within the area is relatively near to the surface and its depth below surface ranges from 0.5 m to 2.5 m depending on the topographic position and the thickness of the surface layer. The seasonal level varies considerably depending upon snowmelt and precipitation (Michalyna 1977).

3.3 Water Intake Rate of the Soil

The water intake rate of the soil was measured in the field after the potatoes had been seeded. A double concentric cylinder ring infiltrometer was used to measure the water intake rate of the soil. Both cylinders were 30 cm high, the diameter of the inner cylinder was 23 cm while the diameter of the outer cylinder was 39 cm. The cylinders were driven about 12 cm into the soil. A float valve was used for a continuous supply of water to the inner cylinder from a reservoir equipped with a piezometric tube. A constant head about 5 cm was maintained in the inner cylinder, while water was added to the outer cylinder as needed. To start the experiment, enough water was supplied instantaneously to both cylinders before the float valve water supply was installed on the inner cylinder. Figure 3.2 illustrates the design of the experiment. The water level in the



Figure 3.2 Measurement of intake rate of the soil by a double concentric cylinder ring infiltrometer.

piezometric tube of the reservoir was read at frequent time intervals. Time was measured with a stop watch.

Soil samples were taken before and after each test for a thermogravimetric determination of the initial and final moisture content of the soil. Samples were taken with a core sampling probe from each 15 cm layer up to a depth of 60 cm, so that four samples were taken from each location.

3.4 The Irrigation System

Irrigation data were collected using a "HiGROmatic Field Hopper" Model 40 spinner-arm self-propelled center-pivot irrigation system. The length of the basic lateral of the unit is 183 m. It is supported by the pivot pyramid and three towers, spaced 61 m apart. A reduced-diameter lateral extends 15 m beyond the third tower. The extension has a Model 150 Nelson endgun at the end. The system was designed to deliver 37.85 $L.s^{-1}$ at 448 kPa pivot pressure. The unit was set to complete one revolution in about 21 hours and to apply 1.91 cm of water.

It has a constant spacing and variable size of nozzle. Sprinkler heads are located 6.1 m apart. Water is pumped from the Assiniboine River through an underground pipeline to the hydrant, located at the northern boundary of the field. From this point, water is supplied to the pivot through a 15-cm portable aluminium irrigation pipeline.

3.5 The Crop and Irrigation Practices

Potatoes were planted on the eastern half of the field on May 11 and 12 in rows, 90 cm apart. The plant-to-plant distance was 33 cm. Before seeding, anhydrous ammonia fertilizer was applied on May 9 at the rate of 135 kg of actual nitrogen per hectare. At the time of seeding liquid ammonium phosphate (10-34-0) was applied with the seed at the rate of 169 $L.ha^{-1}$ resulting in an application of 24 $kg.ha^{-1}$ of nitrogen and 79 $kg.ha^{-1}$ of P_2O_5. The seeding rate was 1.9 tonne per hectare and the variety planted was 'netted gem'. The height of the ridges at the time of blooming was about 30 cm.

Irrigation was applied only to the part of the field planted to potatoes which was about 400 m by 1300 m or 52 ha. Since a three-tower unit can cover only approximately one-fourth of a quarter-section, the unit had to be moved to three different pivot positions to cover the irrigated crop. Usually the system was run so that three revolutions of the system were completed on its central (second) pivot position while only two and one-half revolutions were completed on the northern and southern (i.e. first and third) pivot positions. Such a difficulty generally arises whenever this type of system is used at more than one pivot position. The first irrigation was applied after the first cultivation. Due to poor irrigation scheduling and management, some 25 percent of the plants in the northern pivot position died, because irrigation was applied too late, according to the farmer's own admission. Insecticide was applied three times

by aerial spray.

3.6 Spray Measurement

Catch cans were used to collect sprinkler spray samples. The catch cans, obtained from a local fruit processing plant, were 17.5 cm high and 10.5 cm in diameter with a sharp edge.

The height of the crop at the time of the experiment was about 60 cm and the cans were, therefore, fixed on top of laths about one m long. The tops of the laths were a little below the top edges of the cans to avoid any splash into the cans. With this arrangement, the collecting surfaces of the cans were about 15 cm above the crop canopy as shown in figure 3.3. Weeds taller than the potato plants, were uprooted if there was any possibility of interference with the catching surfaces of the cans. Evaporation from the cans was considered negligible according to the findings of Ali and Barefoot (1978), Barefoot (1978), Frost and Schwalen (1960) and Jones (1974). No evaporation suppressant was, therefore, used in the cans.

3.6.1 Application depth

The method used to collect the spray was very similar to that used by Ring (1975), Ring and Heermann (1978), and recommended by other research workers. The layout of the experiments is illustrated in figure 3.4. In five of the six experiments, three rows of cans were set radially outward along the lateral with an angle of 3° between adjacent rows while in one experiment only two rows were used. The



Figure 3.3 Arrangement of catch cans used to collect sprinkler spray.

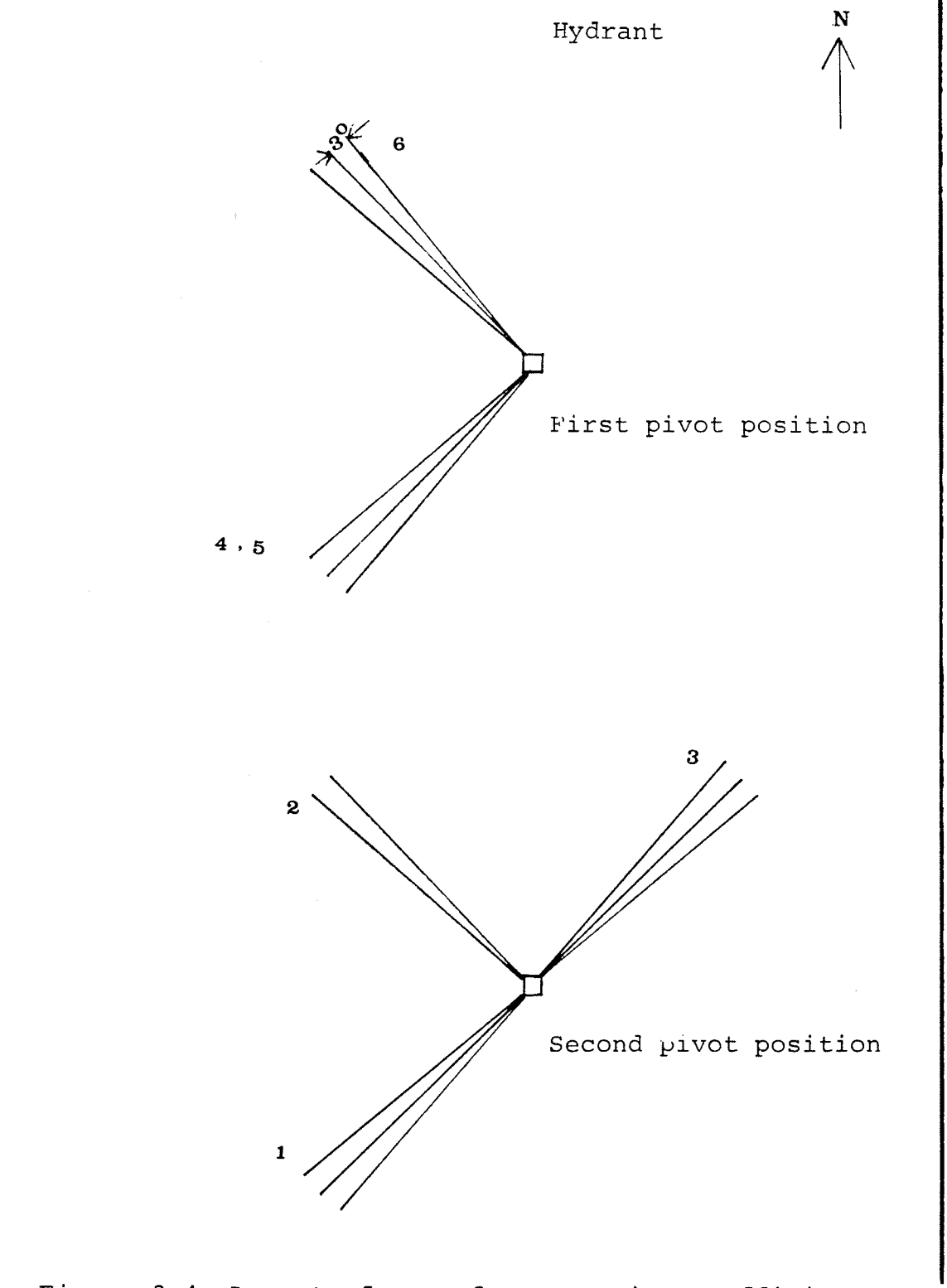


Figure 3.4 Layout of cans for measuring coefficient of uniformity along the lateral.

cans were spaced 5 m apart in each row.

The volume of water collected in the cans was measured immediately after the unit had passed the cans in all the observations except in one. In the latter instance, the cans were left overnight because of the pressure of other tasks. For this experiment three control cans were installed outside the irrigated circle to estimate the evaporation from the catch cans. It also rained that night and the amount of rain was obtained from the nearby weather station of the Canadian Force Bases as well as from the control cans. A negative correction factor was applied to all measurements in this experiment because the amount of rainfall exceeded evaporation.

The volume of water collected in the cans was measured with two graduated cylinders of different sizes. The smaller cylinder was graduated from zero to 100 mL and was precise to 0.5 mL. This cylinder was used to measure smaller amounts of water collected in the cans. The larger cylinder, used for large volumes of water, was graduated from zero to 250 mL and was precise to 1 mL. The equivalent depth was calculated by dividing the measured volume of water by cross-sectional or catch area of the can.

Control cans were also used to determine the difference in the amount of water collected, in cans placed directly on the ground surface, but no difference was observed. It usually took five hours to complete one test.

By installing additional sets of triple rows of cans

elsewhere in the irrigated circle, more than one test could be conducted for the same revolution of the system as shown in figure 3.4.

3.6.2 Application rate

To measure the application rate and time of application, a weighting-type recording rain gage was first used. However, since the system passed over a point about 100 m away from the pivot in less than one hour and the recording pen moved over only a small distance on the graph during the same time, no appreciable results were obtained from this measurement. This could be corrected by changing the timing gears of the gage, but since only one recording rain gage was available for the project and measurements had to be taken at several locations at different distances from the pivot point, a more suitable method using the cans was employed.

Six groups of catch cans were placed at different points along the lateral about 30 m apart. The time when the spray started falling in the cans at each of the observed points, was noted and the volume of water collected in any one can at each position was measured in convenient time intervals ranging from 5 to 15 minutes with the graduated cylinders as described earlier. These measurements were taken at only six locations along the lateral due to constraints of irrigation time and labour.

3.7 Measurement of Speed of the System

The actual speed of a center-pivoted system can be determined by measuring either the angle or the circular distance travelled by the unit with time. In most of the observations, the speed was calculated by measuring the length of the arc with a measuring tape. A number of wooden sticks were fixed at a distance of about 2 m in the track of the first tower for a better measurement of the length of the arc. The time interval was measured with a wrist watch.

3.8 Pressure Measurement

Pressure at the pivot was measured by a standard pressure gage, installed on the lateral at three m from the pivot. The gage was precise to measure 6.9 kPa (1 psi). Pressure was checked at frequent time intervals during each experiment.

3.9 Flow Measurement

Flow into center-pivot systems can be measured by various flow-measuring devices and methods such as inferential flow meters, which give the best results, orifice plates or by measuring the pressure at the pivot (Ring and Heermann 1978). In this project, the pressure gage method was used. However, an attempt was made to double check the flow rates with an orifice meter manufactured in the Agricultural Engineering Department. An orifice plate was installed in a 15-cm-diameter irrigation pipe which was then included into the supply pipeline. Because of practical difficulties the first

measurement was taken only at the end of of the growing season. The results of this measurement, however, were unsatisfactory and subsequent tests were impossible due to poor weather. Therefore, flow had to be determined from the manufacturer's manual on the basis of pressures measured at the pivot.

3.10 Soil Moisture Measurement

Soil samples taken at the time of each infiltration test, were kept in airtight metal cans, until these were weighed in the laboratory before drying. Samples were dried in an oven at 105°C to a constant weight.

3.11 Climatic Data

Weather data such as wind, rainfall, relative humidity and temperature were obtained from the weather station of the Canadian Force Bases[1] approximately 11 km northeast of the experimental field.

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1. Canadian Force Bases. 1978. Weather office Portage la Prairie, Manitoba and personal correspondence.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Coefficient of Uniformity

Uniformity of water application is one of the basics in evaluating any irrigation system. As discussed in section 2.1, the coefficient of uniformity can be calculated by using either equation 2.1 or equation 2.2. Since no one procedure or method has been recommended for the evaluation of center-pivot systems, a computer program was written to calculate the coefficients of uniformity by using both equations. The results are shown in table 4.1.

As argued in section 2.1 and also as pointed out by Heermann and Hein (1968) and Ring and Heermann (1978), the unweighted coefficient of uniformity gives incorrect results. Therefore, only weighted means and weighted coefficients of uniformity, termed as the coefficient of uniformity, will be discussed in the remainder of this report.

4.1.1 Effect of end readings

The weighted factor in equation 2.2 increases with increase of radial distance from the pivot but the depth of water collected in the last few cans decreases rapidly near the end of the irrigated circle. As a result, the coefficient of uniformity is affected seriously near the end of the lateral. A plot of distance from the endgun versus the

TABLE 4.1 COEFFICIENTS OF UNIFORMITY

Experiment	Test Date	Test Time	Distance from Pivot m	Operating Pressure kPa	Coefficient of Uniformity	
					Unweighted %	Weighted %
1	Jul 24	14:00	210	334.4	73.5	75.1
2	Jul 25	11:00	220	403.3	70.0	77.5
3	Jul 25	17:00	180	403.3	73.3	81.3
4	Jul 27	20:00	225	430.9	77.9	77.4
5	Aug 22	10:00	210	451.6	74.6	80.2
6	Aug 25	12:00	225	437.8	71.2	72.8

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coefficient of uniformity for experiment 2, 4 and 6 is shown in figure 4.1 which indicates that the coefficient decreases sharply at a distance beyond 15 m from the endgun or beyond 215 m from the pivot. However, for comparison purposes, all the coefficients will be evaluated up to a radial distance of 210 m from the pivot, since in experiments 1, and 5 observations were taken up to this distance only.

4.1.2 Effect of can spacing

Cans were spaced 5 m apart in each row but the coefficients of uniformity were also calculated for 10-m and 15-m can spacings. These coefficients are listed in table 4.2. The results show that the average coefficients are the same at 5-m and 10-m can spacing but for 15-m spacing, it is 5.6 percent higher than the former spacings.

Statistically, this effect can be examined by using the paired t-test. For each two columns of the coefficients in table 4.2, a t-value was calculated to see the effect of different can spacings at the five-percent level of significance. The calculated and table t-values at their level of significance are given in table 4.3. From these results, it can be concluded that there is no significant difference between the coefficients of uniformity for the 5-m or 10-m can spacings, but the coefficients for the 10-m and 15-m spacings showed a marginal difference at the five-percent level. When the coefficients for 5-m and 15-m can spacings were compared, they also showed a significant difference at the five-percent level.

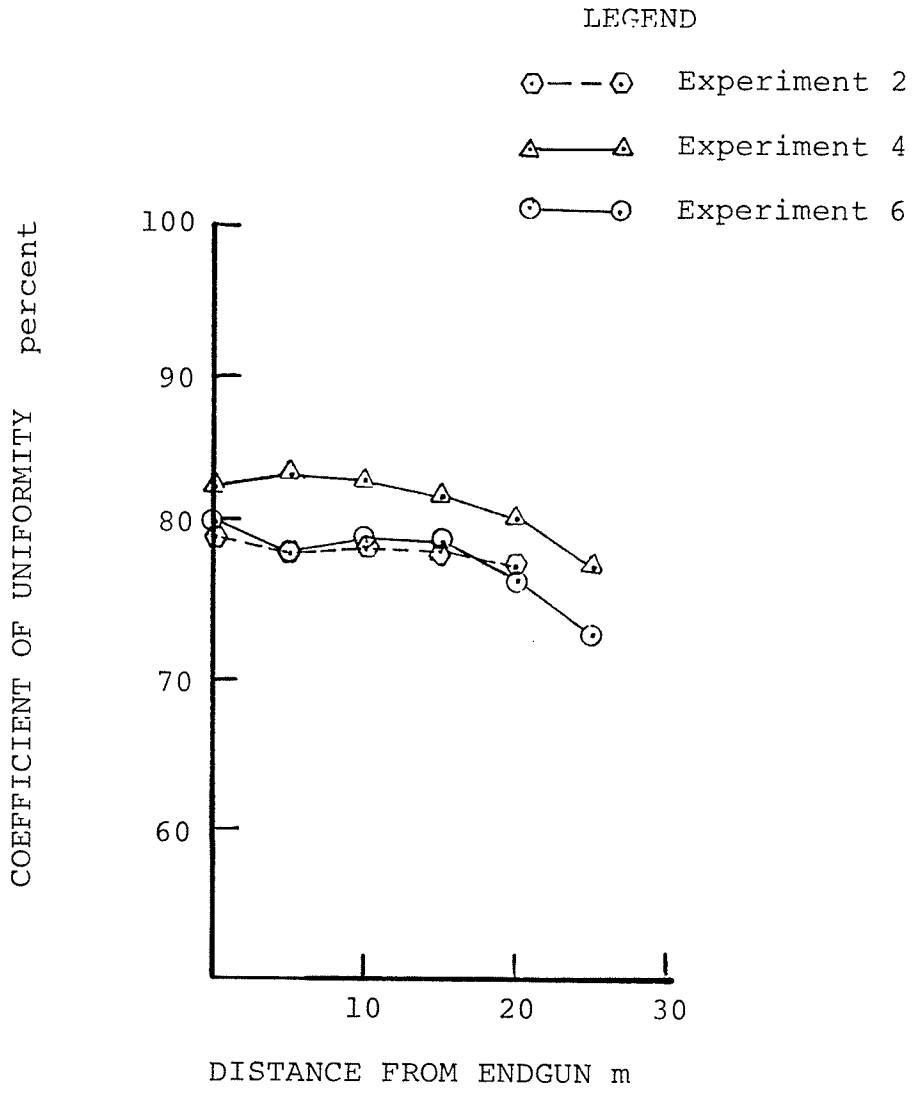


Figure 4.1 Effect of end readings on the coefficient of uniformity.

TABLE 4.2

COEFFICENTS OF UNIFORMITY FOR DIFFERENT SPACING OF CANS AT 210-m RADIAL DISTANCE FROM THE PIVOT

Experiment	Can spacings		
	5 m	10 m	15 m
1	75.1	70.2	87.8
2	78.7	77.4	86.3
3*	81.3	87.0	84.9
4	83.1	83.9	86.0
5	80.2	80.2	85.3
6	79.1	78.7	81.0
Mean	79.6	79.6	85.2

* 180-m radial distance from the pivot

TABLE 4.3

STATISTICAL ANALYSIS FOR DIFFERENT CAN SPACING

Spacings Considered	Degrees of Freedom	Calculated t-value	Table t-value	Level of Significance %
5 m and 10 m	5	2.063	2.015	90
10 m and 15 m	5	2.542	2.571	95
5 m and 15 m	5	3.706	3.163	97.5

4.1.3 Effect of number of rows

As stated before, three rows of cans were placed to collect the spray from the system in all the experiments except in the second experiment. In this experiment, only two rows (Rows A and B) were used. For this experiment, the third row (Row C) was created by averaging the other two rows so as to match this experiment with the other ones. For all experiments, the coefficients of uniformity were calculated for each row. The coefficients were also calculated by combining the data recorded in corresponding cans in the three rows. The results, shown in table 4.4, indicate that there is little or no difference in the coefficients of the different rows in the third experiment. In other experiments this difference varies from 2.4 percent to 7.9 percent. Since radial distance from the pivot in experiment 3 is only 180 m while it is 210 m in the other experiments, it could be hypothesized that the longer radial distance and the endgun effect cause the bigger differences between the coefficients of the rows in the other experiments.

To prove or to disprove this hypothesis, coefficients of uniformity were calculated for radial distances of 200 m and 180 m and presented in tables 4.5 and 4.6, respectively. The results show that the basic relations do not change substantially and that the shorter radial distance in experiment 3 and exclusion of endgun are not the reasons for the smaller difference.

Since the operating pressure did not change during each

TABLE 4.4 COEFFICIENTS OF UNIFORMITY AT 210-m RADIAL DISTANCE FROM THE PIVOT FOR 5-m CAN SPACING

Experiment	Operating Pressure kPa	Coefficients of Uniformity				Max. Difference Between Rows %	Ave. Wind Speed and Direction $km.h^{-1}$	Orientation of Lateral
		ROW A %	ROW B %	ROW C %	AVE. %			
1	334.5	70.2	78.1	73.5	75.1	7.9	12 SE	SW
2	403.3	77.4	79.8	78.5	78.7	2.4	4 WNW	NW
3*	403.3	80.1	80.3	80.1	81.3	0.2	14 WNW	NE
4	430.9	80.0	81.8	83.7	83.1	3.7	14 SW	SW
5	451.7	73.2	77.7	79.4	80.2	6.2	6 SE	SW
6	437.8	78.8	79.4	76.0	79.1	3.4	10 NW	NW
Mean		76.6	79.5	78.5	79.6			

* 180-m radial distance from the pivot

TABLE 4.5

COEFFICIENT OF UNIFORMITY AT 200-m RADIAL DISTANCE FROM THE PIVOT FOR 5-m CAN SPACING

Experiment	Coefficient of Uniformity				Max. Difference Between Rows
	ROW A %	ROW B %	ROW C %	AVE. %	%
1	72.1	80.4	73.7	76.8	8.3
2	78.7	79.8	79.8	79.5	1.1
4	80.2	81.2	84.1	82.7	3.9
5	76.1	78.7	80.9	83.0	4.8
6	80.8	80.7	77.0	80.0	3.8

TABLE 4.6

COEFFICIENT OF UNIFORMITY AT 180-m RADIAL DISTANCE FROM THE PIVOT FOR 5-m CAN SPACING

Experiment	Coefficient of Uniformity				Max. Difference Between Rows
	ROW A %	ROW B %	ROW C %	AVE. %	%
1	78.1	84.1	81.3	82.8	6.0
2	78.4	79.2	79.1	79.0	0.8
3	80.1	80.3	80.1	81.3	0.2
4	82.8	83.6	86.9	85.9	4.1
5	76.8	81.2	82.1	85.4	5.3
6	81.4	83.3	79.0	82.0	4.3

experiment, the only other variable which could have caused the differences is the wind. The six experiments do not give enough data to draw any conclusions about the influence of wind and there seems to be no clear trend. The only remaining and most likely, explanation is that differences were caused by gusty wind conditions in each experiment. This explanation is supported by the analysis of available wind speed data showing a larger difference in wind speeds (6 $km.h^{-1}$) during experiment 1 which has also the highest difference between the coefficients of each row. However, more data would be needed to prove this explanation beyond reasonable doubt. The effect of average wind speed and direction upon the average coefficients of uniformity will be explained later in section 4.3.1.

4.1.4 Effect of operating pressure

The system was designed to deliver 37.85 $L.s^{-1}$ at a pressure of 448 kPa according to the owner-operator's manual. The operating pressures varied from 334 kPa to 452 kPa. Table 4.4 shows that the average coefficient of uniformity increases when the pressure is increased from 334 kPa to 431 kPa through experiments 1 to 4. But when pressure is increased beyond 431 kPa, there is no improvement in the coefficient, and it even decreases (experiments 5 and 6).

4.1.5 Effect of spinner arms

The center-pivot system tested was a spinner-arm-driven unit. The position of spinner arms (towers) in the system

is reflected in figures 4.2 to 4.7. It is obvious from these figures that the spinner arms affect the uniformity of water application seriously. Results of Ring (1975) showed that the spinner-arm-driven system has the lowest coefficient of uniformity as compared to oil or electrically driven systems (table 1.1).

The principle of operation of a spinner arm is shown in figure 4.8. The arms of the spinner which are about one cm in diameter throw water openly without breaking it into droplets. If this water can be split into droplets somehow without affecting the operation of the spinner arms, the uniformity of water application can be improved. A split-head-type nozzle which may be used for this purpose is shown in figure 4.9.

4.2 Application Rate and Intake Rate

The water application rate of a center-pivot system increases towards the end of the unit while the time of water application at a point decreases with increasing distance from the pivot, as is shown in figures 4.10 and 4.11, respectively. The instantaneous application rate patterns at different locations along the lateral are given in figures 4.12 and 4.13. Since the application rate is the highest near the end of a center-pivot system, runoff may occur at this location if it exceeds the soil intake rate. Figure 4.14 shows, however, that the intake rate of the soil is much higher than the water application rate. The intake rate of the soil is so high that even at a higher initial

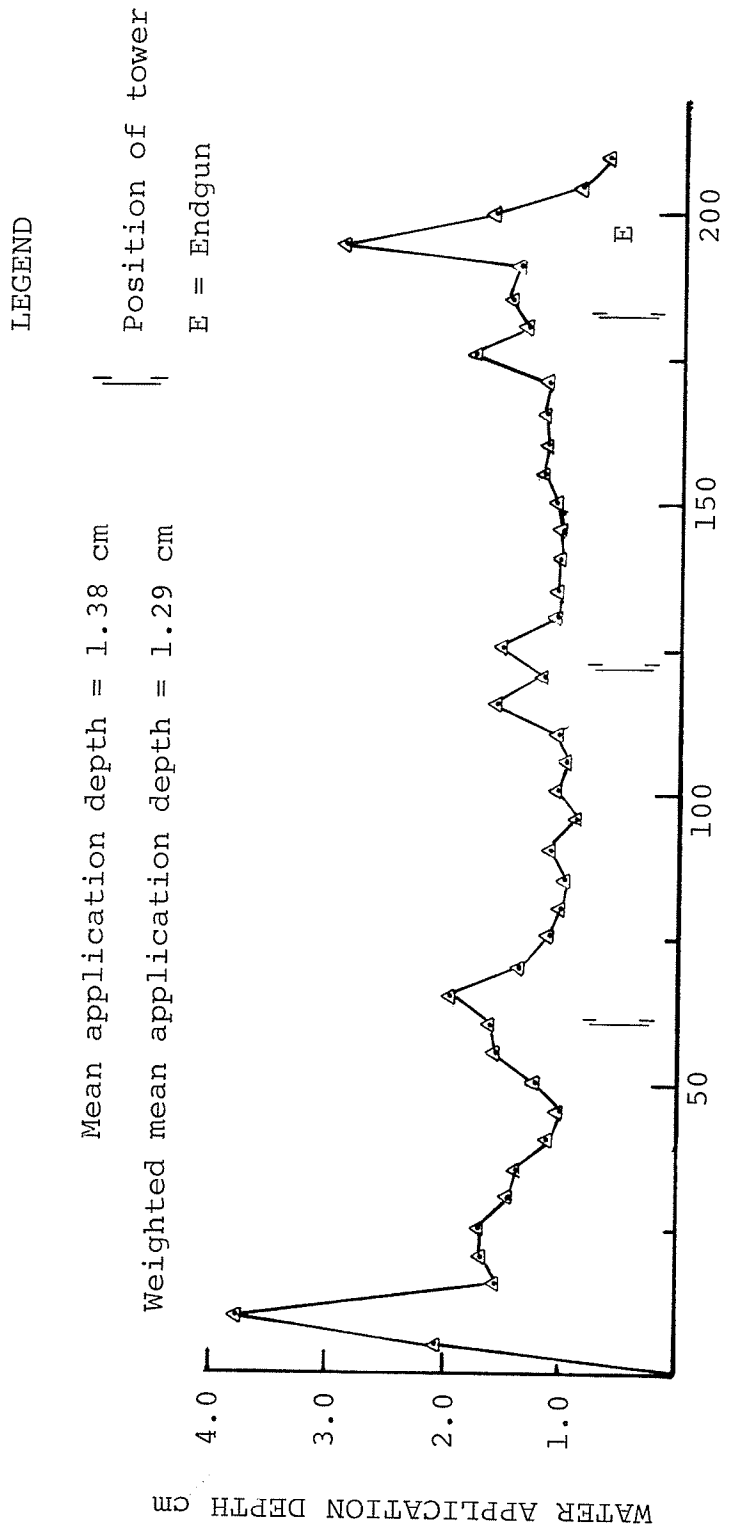


Figure 4.2 Application pattern for experiment 1.

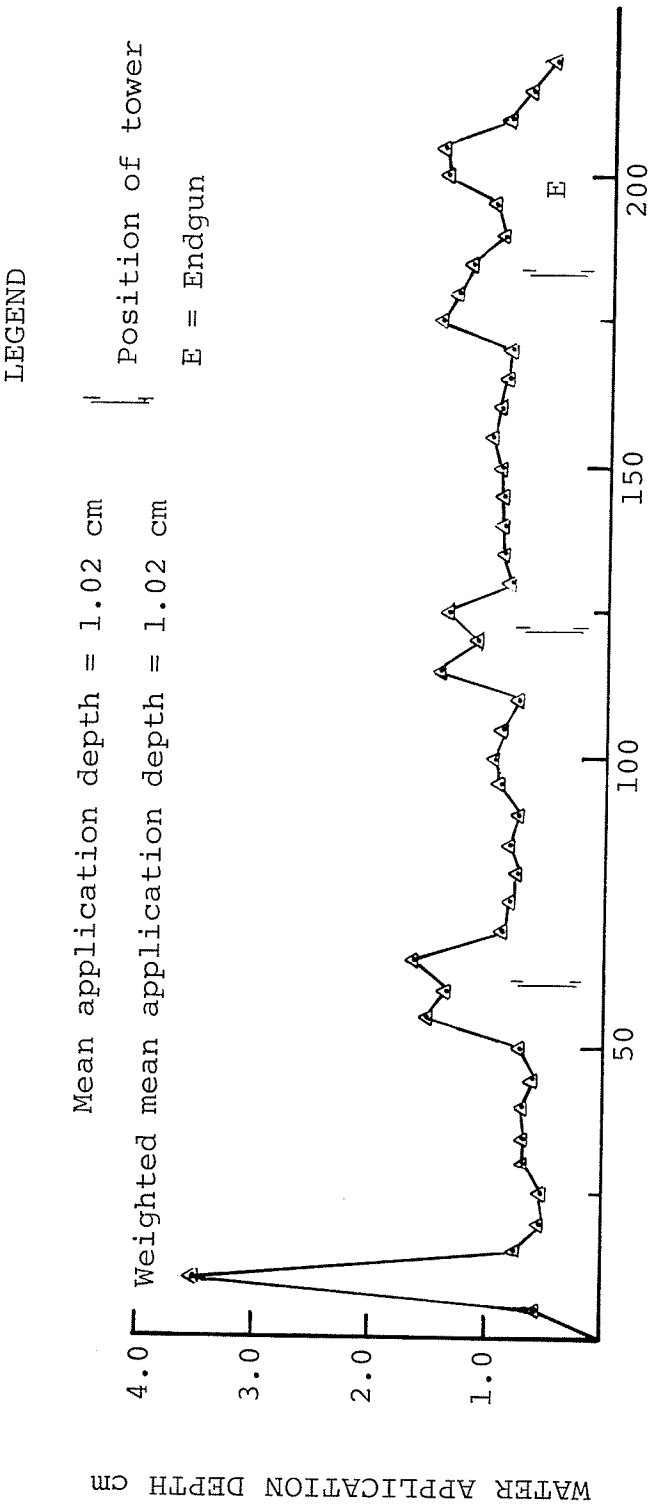


Figure 4.3 Application pattern for experiment 2.

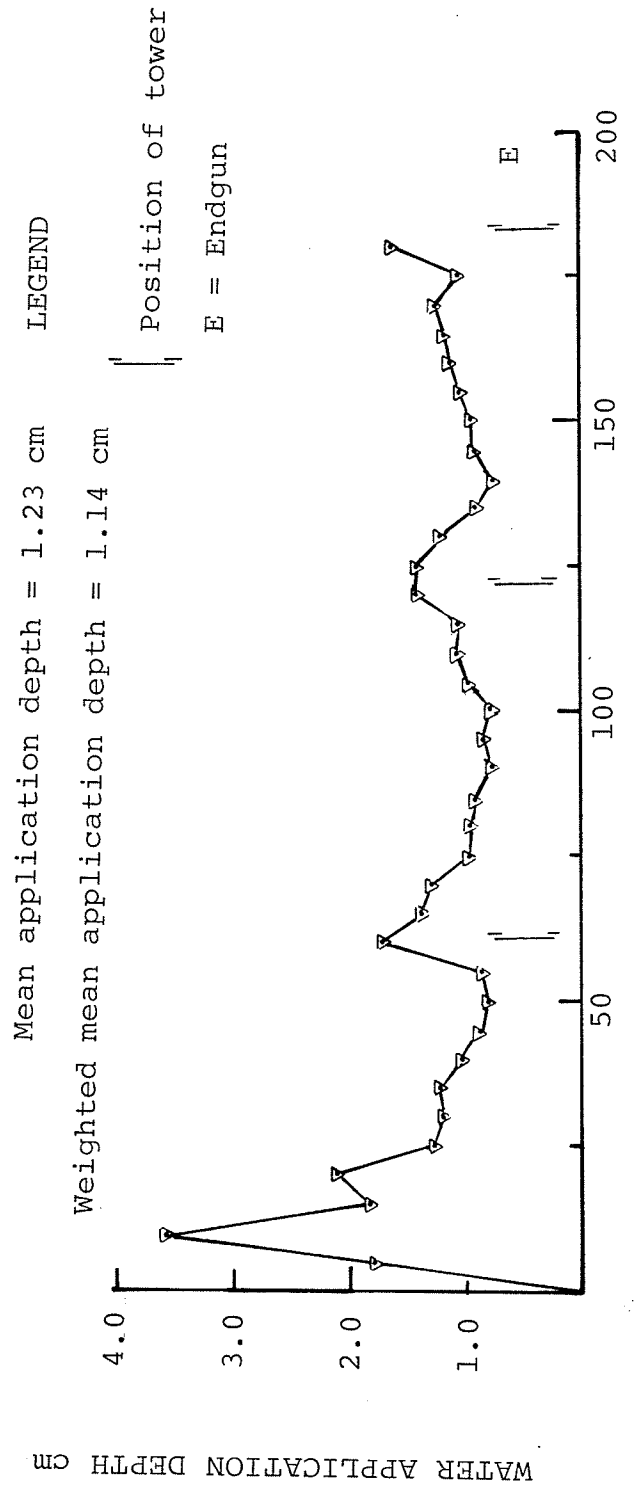


Figure 4.4 Application pattern for experiment 3.

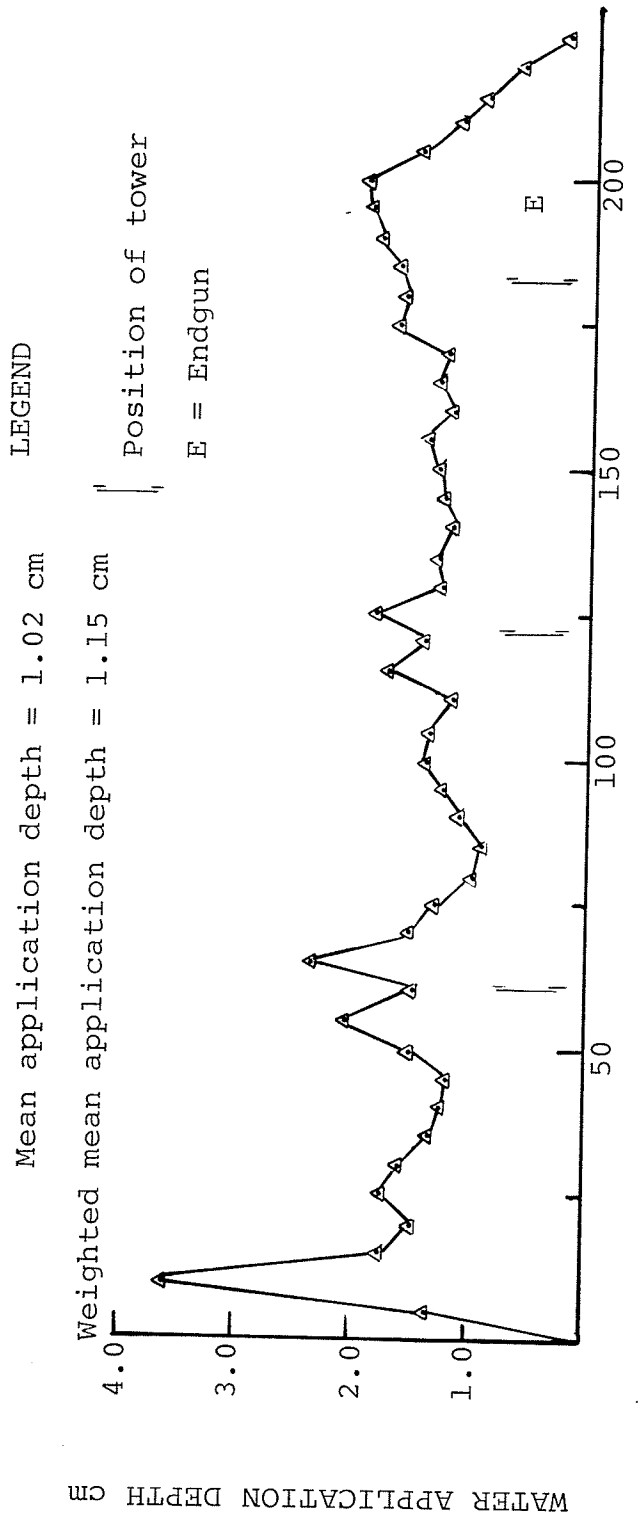


Figure 4.5 Application pattern for experiment 4.

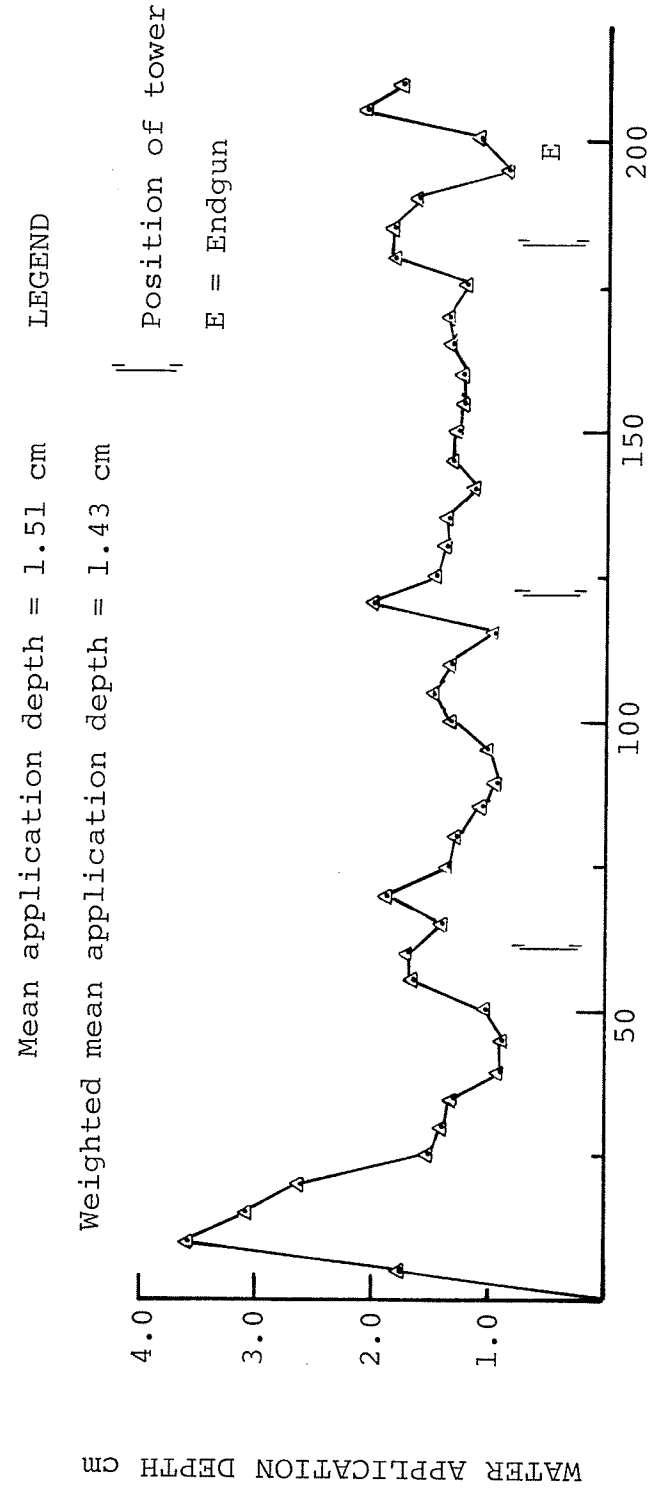


Figure 4.6 Application pattern for experiment 5.

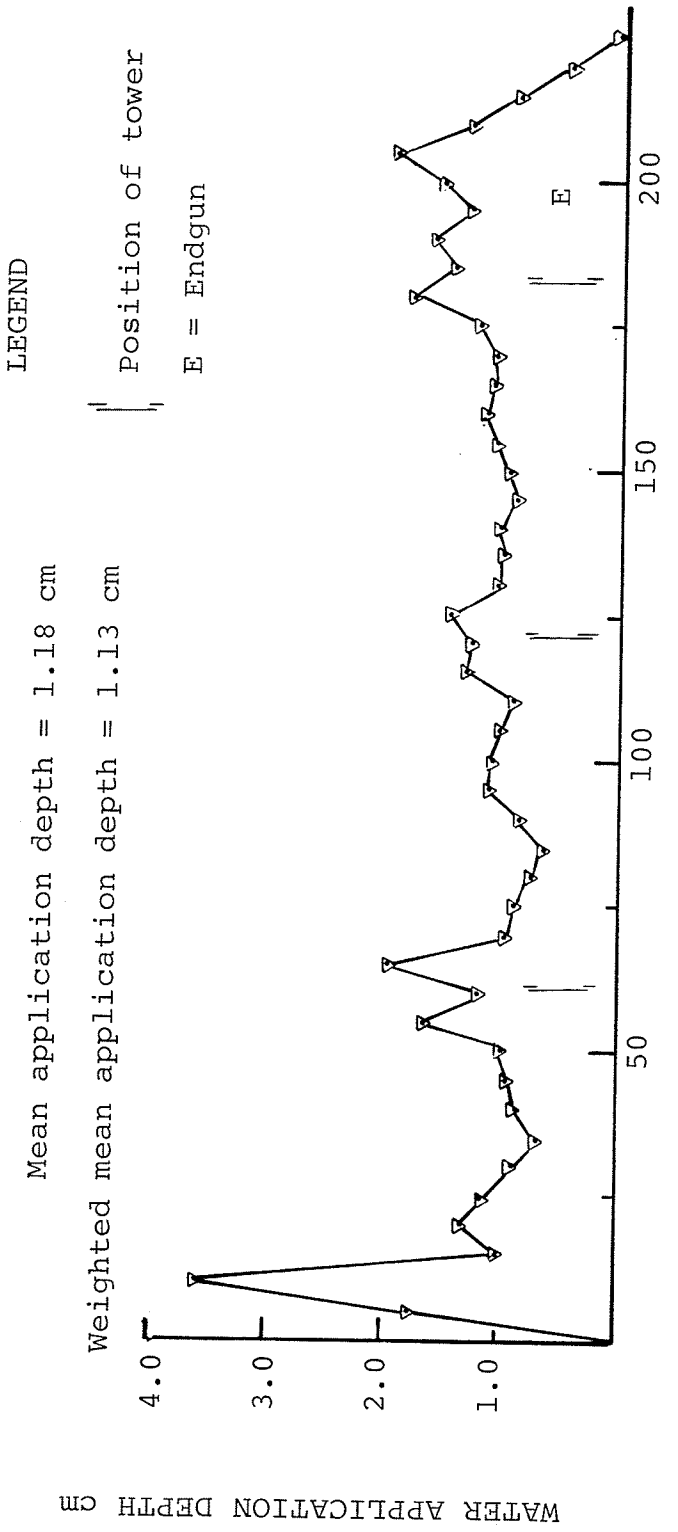


Figure 4.7 Application pattern for experiment 6.

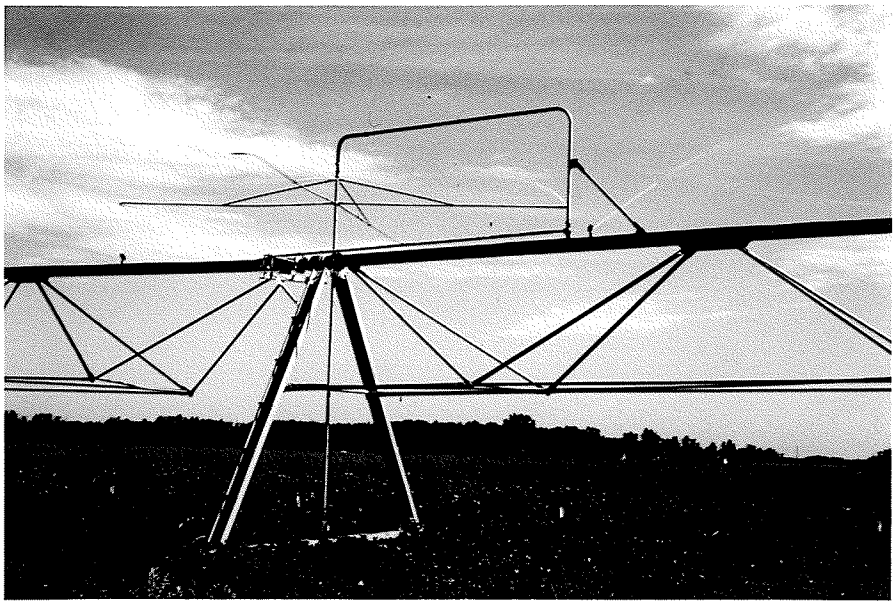


Figure 4.8 Spinner arms.

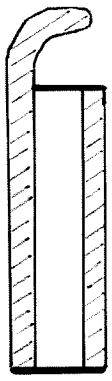


Figure 4.9 Section of a split-head-type nozzle.

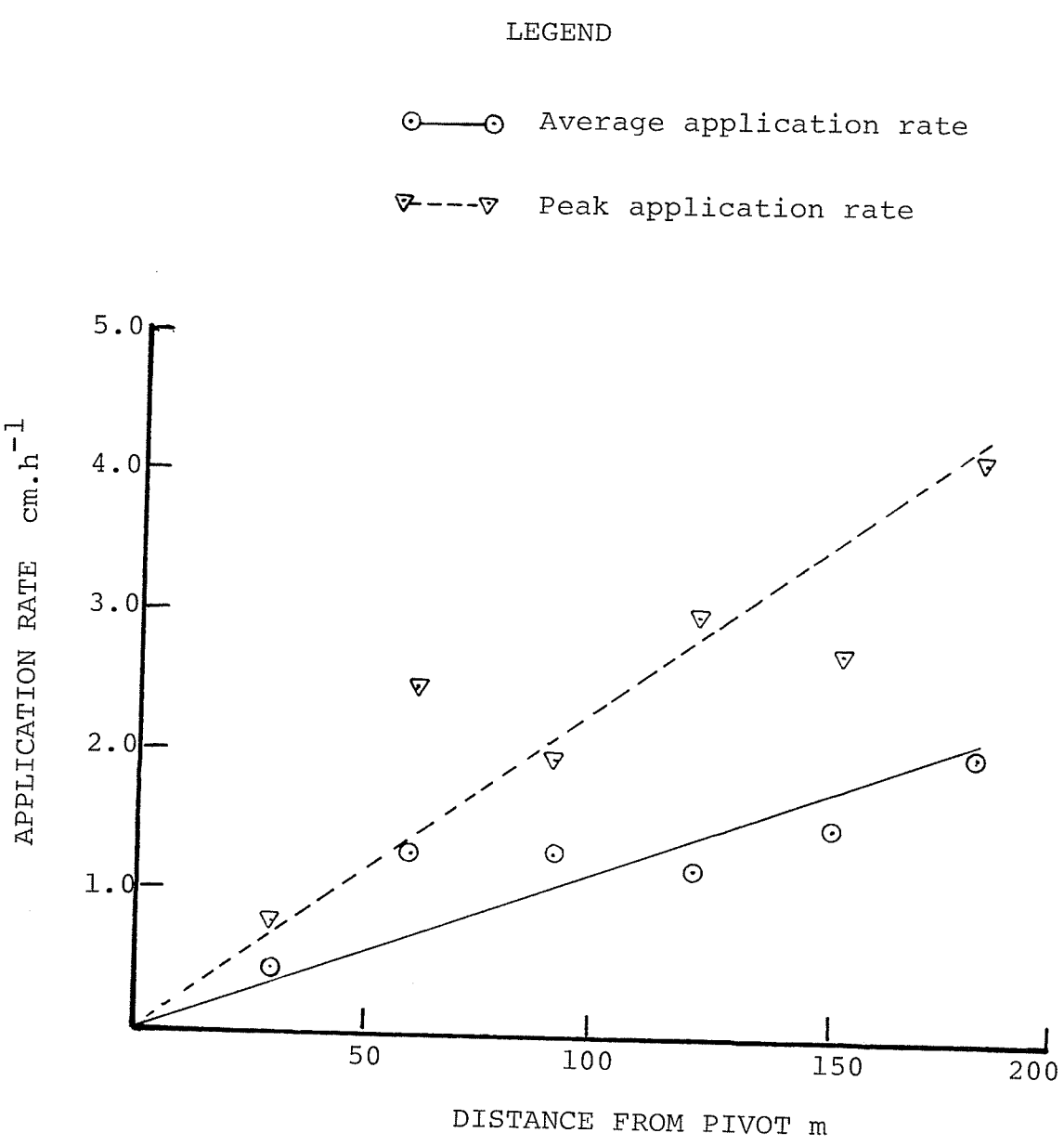


Figure 4.10 Water application rates along the lateral.

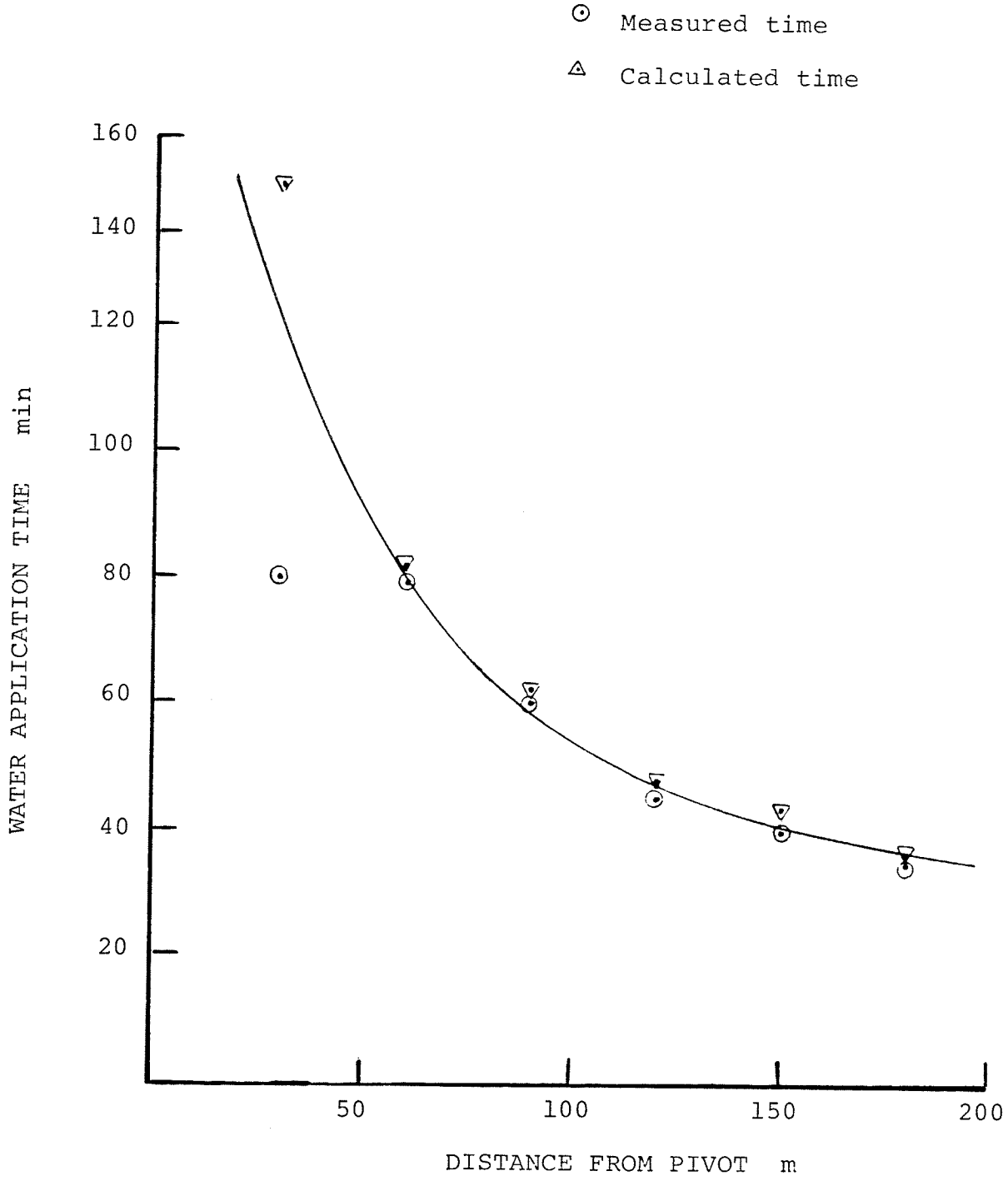


Figure 4.11 Water application time along the lateral.

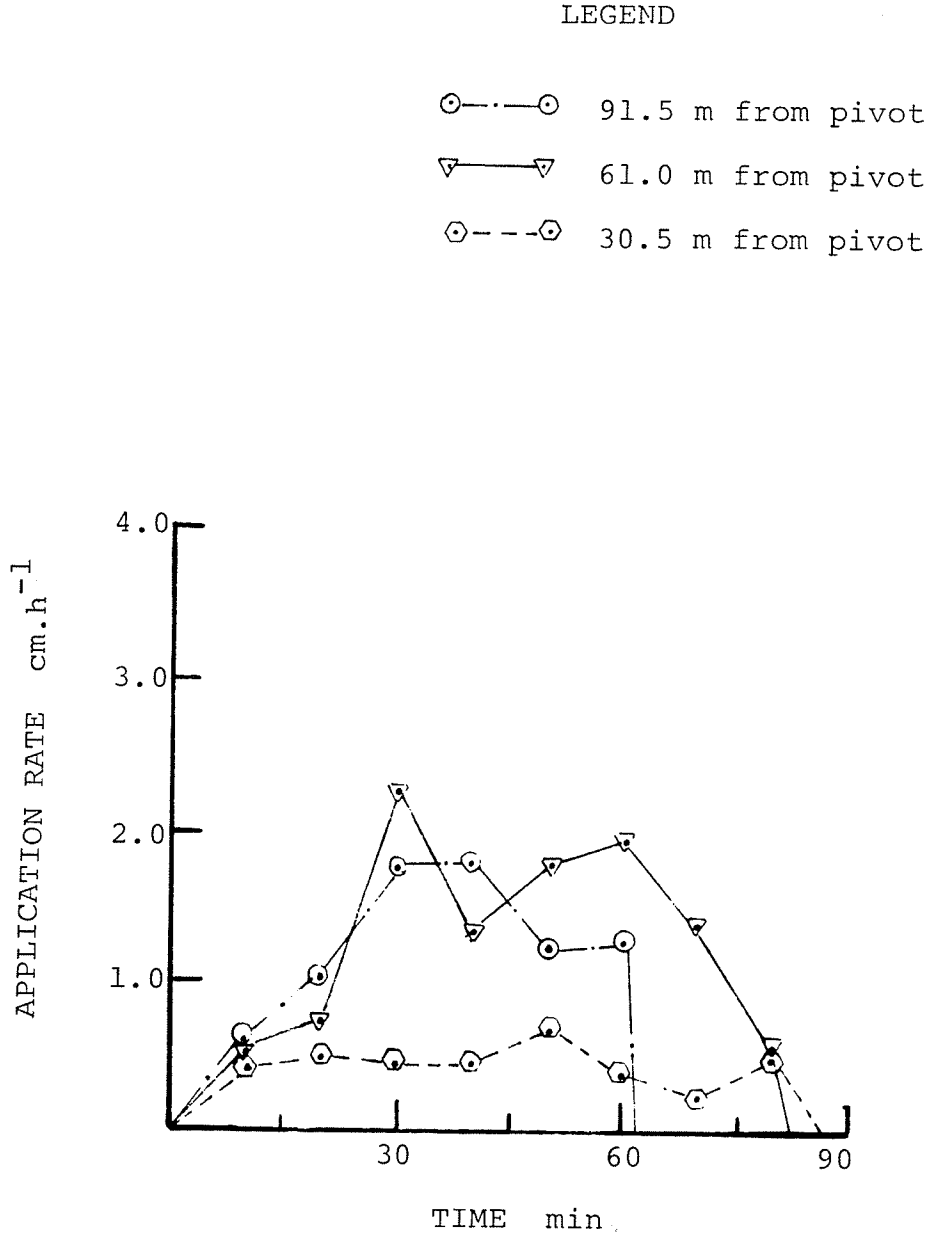


Figure 4.12 Application patterns at 30.5 m, 61.0 m and 91.5 m from the pivot.

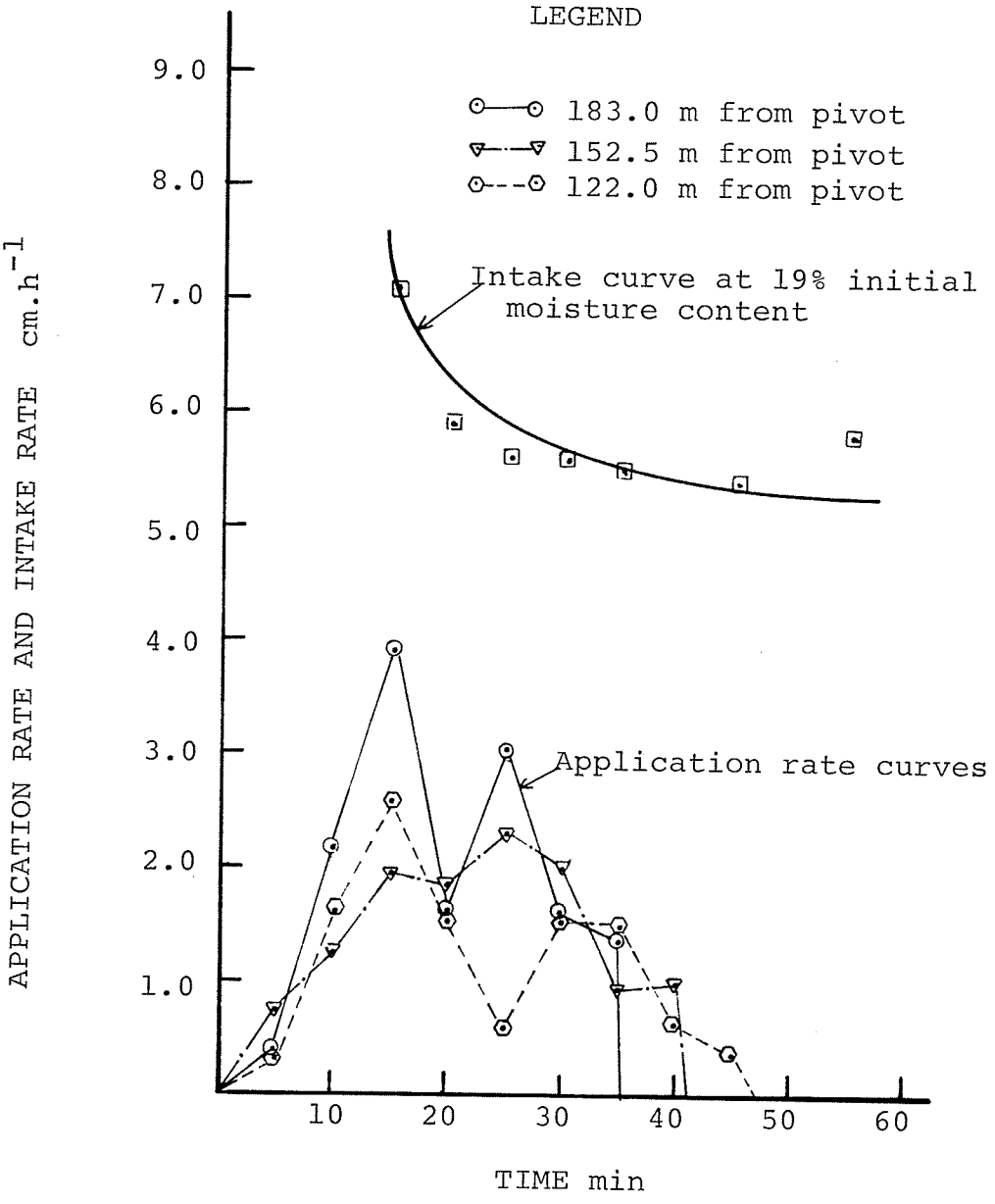


Figure 4.13 Applications patterns at 122.0 m, 152.5 m and 183.0 m from the pivot and intake rate curve.

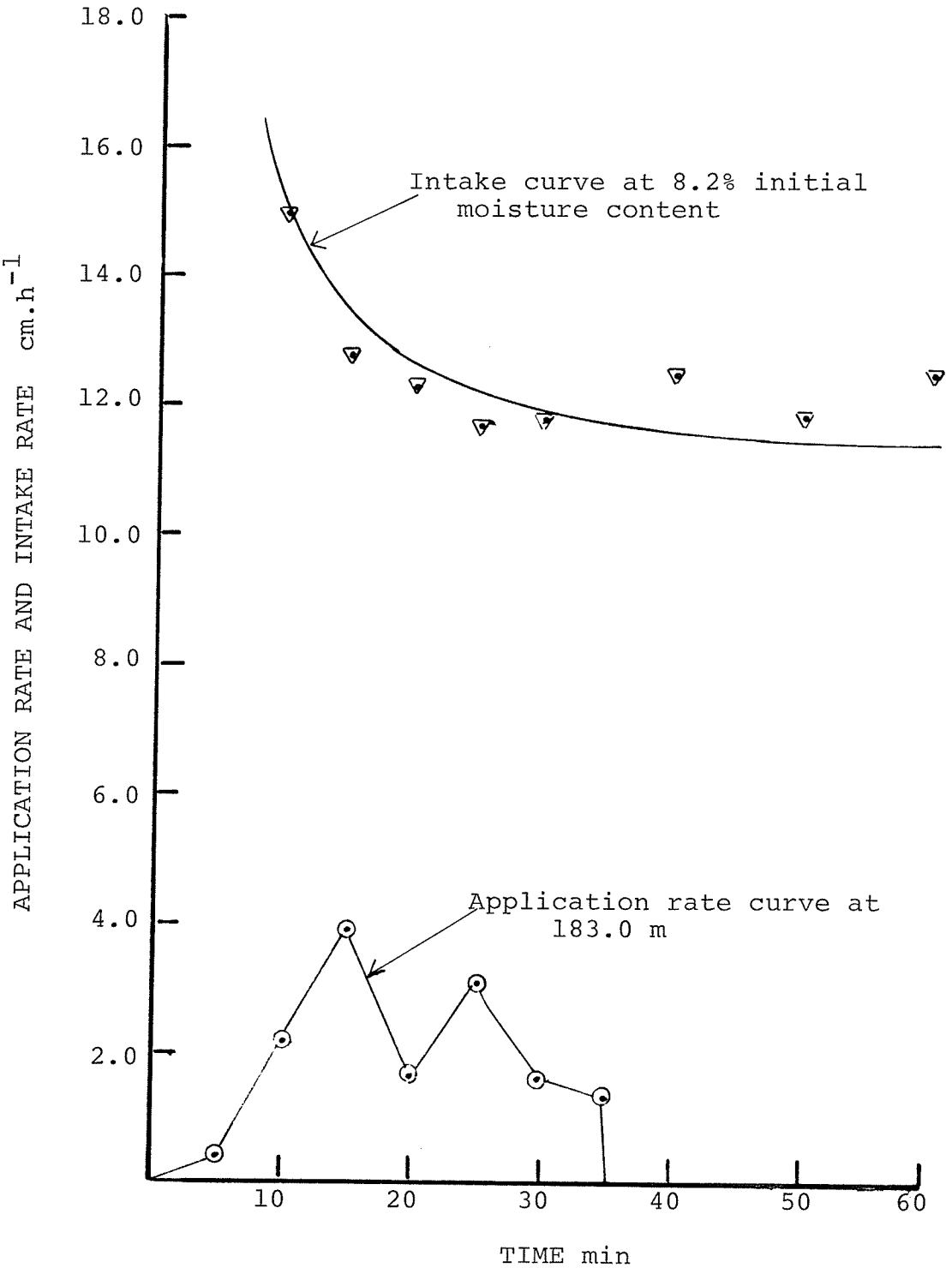


Figure 4.14 Intake rate of the soil before irrigation and application rate at 183.0 m from the pivot.

moisture content, the final intake capacity of the soil is still higher than the application rates encountered (figure 4.13).

The infiltration data show a tremendous variation in the intake characteristics of the soil within the field (table 4.7). This variation may be due to the textural changes in the surface layer from coarse sand to very fine sand. The advantage of the high intake rate of the soil can be utilized by increasing the water application rates of the system through the use of low-pressure, spray-type nozzles instead of the high-pressure impact-type sprinkler heads. The spray-type nozzles also have less evaporation loss.

4.3 Application Losses

The water application loss considered here is defined as the difference between the amount of water collected in the cans and the volume of water leaving the system. Part of the loss is due to water drift by air and part is evaporation but the two components of water losses were not studied independently.

By continuity, the amount of water entering the system is equal to the amount of water leaving it. The flow into the system was estimated from the owner-operator's manual on the basis of recommended pressure at the pivot, which was 448 kPa and the corresponding discharge was 37.85 $L.s^{-1}$. Time to complete one revolution of the unit was calculated from the measured speed of the lateral so that the volume of water delivered by the system per revolution is given by

TABLE 4.7

INFILTRATION DATA BEFORE IRRIGATION AT 8.2 PERCENT INITIAL MOISTURE CONTENT

Time Elapsed min	Infiltration Rate $cm.h^{-1}$ Test Numbers						Average
	3	4	5	6	9	10	
2	123.0	138.0	198.0	121.5	231.0	171.0	163.8
5	16.8	39.0	34.8	55.0	46.0	43.0	30.2
10	12.0	21.6	9.0	16.8	23.4	17.4	15.1
15	5.4	18.0	9.0	12.6	19.2	12.6	12.8
20	7.2	18.0	7.8	10.8	18.0	12.0	12.3
25	6.0	15.0	7.2	12.0	18.6	11.4	11.7
30	4.8	18.0	7.2	10.2	19.2	11.4	11.8
40	6.0	18.6	8.4	11.0	19.5	11.7	12.5
50	5.0	17.4	7.2	10.5	20.1	11.1	11.9
60	6.6	16.5	7.8	12.3	20.4	11.7	12.6

the following relationship:

$$V_1 = QT \qquad 4.1$$

where: V_1 = volume of water delivered by the system per revolution, $[L^3]$

Q = discharge at the pivot, $[L.^3T^{-1}]$

T = time to complete one revolution, $[T]$.

The volume of water collected in the cans per revolution was calculated by the following equation:

$$V_2 = \sum_{i=1}^{N} 2\pi R_s D_s S \qquad 4.2$$

where V_2 is the volume collected in the cans per revolution and the other symbols are the same as in equation 2.2 but the number of observation, N, must include the end observations as well. Thus the application loss, E as defined above is given by the following simple equation:

$$E = \frac{V_1 - V_2}{V_1} \times 100 \qquad 4.3$$

These calculations were done only for the last three experiments since, in the other experiments the operating pressure was lower than the recommended pressure and, as a result, the flow rate (and the volume V_1) could not be estimated. Table 4.8 shows these results and the weather data at the time of each experiment.

TABLE 4.8 APPLICATION LOSSES AND WEATHER DATA

Experiment	Test Date	Test Time	Temperature °C	Relative Humidity %	Average Wind Speed $km.h^{-1}$	Volume of Water Collected m^3	Losses %
1	Jul 24	14:00	28	61	12	2057	*
2	Jul 25	11:00	24	60	4	1627	*
3	Jul 25	17:00	29	41	14	1778	*
4	Jul 27	20:00	19	60	14	2177	18.6[3]
5	Aug 22	10:00	9	74	6	2276	18.5[3]
6	Aug 25	12:00	25	60	10	1796	34.4[3]

* Not calculated because the flow rate could not be determined

1. Estimated discharge = 37.85 $L.s^{-1}$

2. Average speed of the system = 8.0 $cm.min^{-1}$

3. Average loss = 23.8 percent

4.3.1 Wind effect

Wind has usually two effects. First it increases application losses due to both drifting and evaporation, and secondly it distorts the water distribution pattern. In this study only the latter effect was noted.

Since the differences between the coefficients of different rows of the same experiment are not caused by the operating pressure or by the radial distance, the only factor which seems to be responsible is wind as explained in section 4.1.3. However, since the lateral of a center-pivot system changes its position continuously and the same is true for wind speed and direction, it is not easy to interpret the wind effect. It would require a very detailed study to do it. Since the values of wind speed and other climatic variables listed in tables 4.4 and 4.8 are the averages during the hour during which the unit was passing over the cans and since the positions of the lateral are also only approximate, any conclusion drawn from the interpretation of these values would be only rough.

It is generally believed in sprinkler irrigation systems other than center-pivot that cross winds causes more distortion of the patterns than if the wind is parallel to the lateral. The same seems to be also true for a center-pivot irrigation system. Tables 4.4, 4.5 and 4.6 show that when the wind is perpendicular to the lateral even at lower speeds, it causes more distortion and this is reflected by the coefficients of uniformity (experiments 5 and 6).

However, experiment 3, in which the wind was almost perpendicular to the lateral, does not support this general observation.

Due to an insufficiency of data collected, no correlation of application losses is possible with other climatic variables.

CHAPTER V

CONCLUSIONS

Based on the results obtained from the analysis of data, the following conclusions are drawn.

1. The average coefficient of uniformity of the tested center-pivot system was 80 percent at a radial distance of 210 m from the pivot.
2. At about 20 m beyond the endgun the coefficient of uniformity decreased significantly.
3. A can spacing of 10 m was found to be as good as 5 m for measuring the coefficient of uniformity.
4. At can spacing of 15 m the coefficient of uniformity was found to be six percent higher than at 5-m or 10-m can spacings.
5. The system tested was spinner-arm-driven. The spinner arms were found to have an adverse effect on the uniformity of water application.
6. The intake rate of the soil showed a great variation in the field.
7. The average intake rate of the soil was about three times higher than the peak application rate and, therefore, no potential for runoff exists.
8. The application loss was found to be 24 percent at an average wind speed of 10 $km.h^{-1}$.

CHAPTER VI

RECOMMENDATIONS

The following recommendations are made on the basis of results obtained in this study.

1. Since can spacings of 5 m and 10 m yield similar coefficients of uniformity, can spacings of 10 m can be used for economy.
2. Since the observations some distance beyond the endgun affect the coefficient adversely, it is important to report over what radial distance the coefficient of uniformity was calculated.
3. For soils of high intake rate, low-pressure spray-type nozzles should be used to reduce the operating costs and evaporation losses.
4. The use of the split-head-type nozzle is suggested to improve the non-uniformity of water application caused by spinner arms.
5. Wind speed, wind direction and variability affect the uniformity of water application seriously. To explore these effects, a detailed study should be carried out.

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APPENDIX A

Data for Coefficient of Uniformity

TABLE A-1 DATA COLLECTED FOR EXPERIMENT 1

Distance From Pivot m	Volume* of Water Collected mL		
	ROW A	ROW B	ROW C
5.0	172.0	173.0	198.0
10.0	328.0	328.0	331.0
15.0	122.0	127.0	157.0
20.0	127.0	140.0	172.0
25.0	147.0	146.0	152.0
30.0	124.0	127.0	125.0
35.0	124.0	119.0	118.0
40.0	100.0	98.0	95.0
45.0	88.0	95.0	89.0
50.0	103.0	114.0	100.5
55.0	121.0	130.0	155.0
60.0	150.0	133.0	141.0
65.0	198.0	171.0	142.0
70.0	106.0	113.0	139.0
75.0	91.0	102.0	94.0
80.0	88.0	87.0	86.0
85.0	96.0	84.0	71.0
90.0	103.0	97.0	90.0
95.0	96.0	85.0	47.5
100.0	88.0	98.0	87.5
105.0	73.0	84.0	93.5
110.0	95.0	83.0	100.0
115.0	137.0	128.0	148.0
120.0	74.0	106.0	125.0
125.0	144.5	155.0	100.0
130.0	94.0	98.0	86.0
135.0	90.0	98.0	95.0
140.0	86.0	95.0	89.0
145.0	56.0	112.0	99.0
150.0	78.0	110.0	94.0
155.0	92.0	124.0	92.0
160.0	83.0	117.0	96.0
165.0	84.0	121.0	97.0
170.0	79.0	118.0	92.0
175.0	151.0	159.0	155.0
180.0	113.0	134.0	97.0
185.0	115.0	128.0	141.0
190.0	135.0	115.0	112.0
195.0	255.5	250.0	260.0
200.0	142.0	145.0	144.0
205.0	77.0	75.0	80.0
210.0	44.5	60.0	74.0

Operating pressure = 334.7 kPa
Speed of the lateral = 7.0 $cm.min^{-1}$
Time to complete one revolution = 22.7 h

* Cross-sectional area of the can = 87.0 cm^2

TABLE A-2 DATA COLLECTED FOR EXPERIMENT 2

Distance From Pivot m	Volume of Water Collected mL		
	ROW A	ROW B	ROW C*
5.0	57.0	42.0	50.0
10.0	297.0	315.0	306.0
15.0	62.0	67.0	65.0
20.0	44.0	48.0	46.0
25.0	45.0	54.0	50.0
30.0	54.0	65.0	60.0
35.0	55.0	64.0	60.0
40.0	55.0	64.0	60.0
45.0	52.0	52.0	52.0
50.0	60.0	63.0	62.0
55.0	131.0	132.0	131.0
60.0	100.0	135.0	118.0
65.0	146.0	139.0	143.0
70.0	84.0	74.0	77.0
75.0	69.0	74.0	72.0
80.0	66.0	66.0	66.0
85.0	78.0	66.0	72.0
90.0	64.0	68.0	66.0
95.0	77.0	81.0	79.0
100.0	86.0	84.0	85.0
105.0	80.0	80.0	80.0
110.0	70.0	65.0	67.0
115.0	120.0	134.0	127.0
120.0	106.0	96.0	101.0
125.0	130.0	114.0	122.0
130.0	80.0	68.0	74.0
135.0	84.0	76.0	80.0
140.0	84.0	78.0	81.0
145.0	83.0	79.0	81.0
150.0	87.0	79.0	83.0
155.0	94.0	85.0	89.0
160.0	90.0	78.0	89.0
165.0	76.0	80.0	78.0
170.0	80.0	74.0	77.0
175.0	144.0	116.0	130.0
180.0	120.0	111.0	116.0
185.0	110.0	100.0	105.0
190.0	79.0	88.0	84.0
195.0	100.0	84.0	82.0
200.0	126.0	124.0	125.0
205.0	146.0	112.0	129.0
210.0	80.0	78.0	79.0
215.0	65.0	62.0	63.5
220.0	45.0	46.0	45.5

Operating pressure = 403.3 kPa
Speed of the lateral = 7.8 $cm.min^{-1}$
Time to complete one revolution = 20.5 h
* Generated data

TABLE A-3 DATA COLLECTED FOR EXPERIMENT 3

Distance From Pivot m	Volume of Water Collected mL		
	ROW A	ROW B	ROW C
5.0	145.0	149.0	169.0
10.0	312.0	316.0	310.0
15.0	218.0	150.0	110.0
20.0	164.0	252.0	134.0
25.0	90.0	113.0	128.0
30.0	102.0	103.0	110.0
35.0	96.0	119.0	108.0
40.0	82.0	88.0	108.0
45.0	83.0	77.0	72.0
50.0	70.0	73.0	72.0
55.0	79.0	78.0	74.0
60.0	163.0	144.0	145.0
65.0	116.0	123.0	128.0
70.0	114.0	118.0	105.0
75.0	85.0	92.0	80.0
80.0	82.0	89.0	79.0
85.0	83.0	84.0	75.0
90.0	68.0	76.0	60.0
95.0	75.0	74.0	70.0
100.0	80.0	61.0	68.0
105.0	84.0	98.0	79.0
110.0	106.0	81.0	98.0
115.0	112.0	85.0	83.0
120.0	147.0	142.0	87.0
125.0	131.0	112.0	125.0
130.0	126.0	95.0	101.0
135.0	82.0	73.0	80.0
140.0	73.0	63.0	55.0
145.0	84.0	79.0	74.0
150.0	89.0	75.0	82.0
155.0	91.0	90.0	95.0
160.0	97.0	96.0	99.0
165.0	104.0	102.0	105.0
170.0	110.0	108.0	113.0
175.0	91.0	95.0	90.0
180.0	142.0	145.0	140.0

Operating pressure = 403.3 kPa

Speed of the lateral = 7.8 $cm.min^{-1}$

Time to complete one revolution = 20.5 h

TABLE A-4 DATA COLLECTED FOR EXPERIMENT 4

Distance From Pivot m	Volume of Water Collected mL		
	ROW A	ROW B	ROW C
5.0	108.0	115.0	130.0
10.0	325.0	314.0	308.0
15.0	147.0	156.0	153.0
20.0	124.0	136.0	127.0
25.0	154.0	151.0	152.0
30.0	136.5	124.5	160.0
35.0	120.5	107.0	125.5
40.0	104.0	110.0	117.5
45.0	111.0	97.0	106.0
50.0	127.5	138.5	129.0
55.0	184.0	186.0	175.0
60.0	141.0	134.0	114.0
65.0	194.0	207.0	222.0
70.0	207.5	100.5	98.0
75.0	101.0	118.5	125.5
80.0	99.0	78.5	78.0
85.0	78.5	74.5	78.0
90.0	86.0	104.0	99.0
95.0	113.5	94.0	122.5
100.0	116.0	126.0	120.5
105.0	115.0	119.0	123.0
110.0	101.0	112.0	92.0
115.0	149.0	153.0	152.0
120.0	124.0	110.0	137.0
125.0	172.0	152.0	157.0
130.0	98.0	101.0	135.0
135.0	99.0	121.0	126.0
140.0	103.0	94.0	120.0
145.0	111.0	113.0	113.0
150.0	121.5	108.5	122.0
155.0	116.0	127.0	127.0
160.0	123.0	84.5	111.0
165.0	110.5	124.0	121.0
170.0	98.0	112.0	120.0
175.0	157.0	145.0	143.0
180.0	131.5	142.5	142.5
185.0	172.0	137.0	133.0
190.0	152.5	170.0	163.0
195.0	164.0	174.5	164.0
200.0	161.5	165.0	192.0
205.0	113.0	120.0	159.0
210.0	88.0	104.0	105.0
215.0	76.0	83.5	84.0
220.0	38.0	63.0	65.0
225.0	21.5	17.0	26.5

Operating pressure = 430.9 kPa
Speed of the lateral = 8.6 $cm.min^{-1}$
Time to complete one revolution = 19.6 h

TABLE A-5 DATA COLLECTED FOR EXPERIMENT 5

Distance From Pivot m	Volume of Water Collected mL		
	ROW A	ROW B	ROW C
5.0	145.0	149.0	169.0
10.0	312.0	316.0	310.0
15.0	278.0	263.0	270.0
20.0	244.0	210.5	231.0
25.0	132.0	131.0	132.0
30.0	138.0	119.0	109.0
35.0	117.0	98.0	125.0
40.0	74.0	82.0	82.0
45.0	87.0	73.5	74.5
50.0	91.5	84.0	93.0
55.0	169.0	137.0	128.0
60.0	162.0	93.2	183.0
65.0	153.5	101.0	114.5
70.0	132.0	179.0	193.0
75.0	100.5	122.0	126.5
80.0	116.0	103.0	118.0
85.0	68.5	104.0	106.0
90.0	58.0	84.0	102.0
95.0	57.0	85.0	126.0
100.0	100.0	121.0	135.0
105.0	105.0	144.0	140.0
110.0	98.0	143.0	107.0
115.0	87.0	85.0	82.0
120.0	140.5	193.0	193.0
125.0	96.0	146.0	147.0
130.0	92.5	141.0	126.0
135.0	64.0	86.0	207.0
140.0	85.0	112.0	106.5
145.0	90.0	135.0	122.0
150.0	84.5	132.0	127.0
155.0	75.5	122.0	126.5
160.0	80.0	123.0	126.0
165.0	89.0	148.0	120.0
170.0	91.0	149.0	120.0
175.0	89.0	122.0	106.0
180.0	153.0	168.5	161.0
185.0	134.0	189.0	162.0
190.0	118.5	171.0	145.0
195.0	55.0	102.0	79.0
200.0	109.0	89.0	94.0
205.0	185.0	182.0	184.0
210.0	139.0	188.0	163.0

Operating pressure = 451.6 kPa
Speed of the lateral = 7.8 $cm.min^{-1}$
Time to complete one revolution = 20.5 h

TABLE A-6 DATA COLLECTED FOR EXPERIMENT 6

Distance From Pivot m	Volume of Water Collected mL		
	ROW A	ROW B	ROW C
5.0	145.0	149.0	169.0
10.0	312.0	316.0	310.0
15.0	95.0	89.0	77.0
20.0	122.0	114.0	115.0
25.0	91.0	107.0	105.0
30.0	83.0	72.0	78.0
35.0	55.0	52.0	61.0
40.0	73.5	73.0	74.0
45.0	80.0	86.0	80.0
50.0	88.0	81.0	83.0
55.0	156.0	143.0	131.0
60.0	96.5	102.0	113.0
65.0	159.0	183.0	170.0
70.0	91.5	84.0	72.0
75.0	82.0	80.0	66.5
80.0	74.5	72.5	46.0
85.0	48.5	44.5	67.0
90.0	68.0	64.0	91.0
95.0	109.0	99.0	89.5
100.0	104.5	98.0	76.0
105.0	96.5	91.5	76.0
110.0	85.0	87.0	67.5
115.0	115.0	123.5	106.0
120.0	131.0	105.5	98.0
125.0	130.5	116.5	132.5
130.0	91.0	100.0	82.0
135.0	92.5	87.0	82.0
140.0	94.0	89.0	89.0
145.0	81.0	80.0	75.0
150.0	86.5	84.5	73.5
155.0	90.5	99.0	95.0
160.0	107.0	106.5	88.5
165.0	102.0	96.0	93.0
170.0	99.0	93.0	91.0
175.0	107.0	95.0	120.0
180.0	166.5	142.5	157.5
185.0	124.0	130.5	122.0
190.0	140.0	142.5	136.0
195.0	106.0	112.0	121.0
200.0	139.0	135.0	124.5
205.0	183.0	161.0	165.0
210.0	117.0	122.5	93.5
215.0	78.5	85.0	71.5
220.0	47.5	43.0	25.5
225.0	3.0	3.0	2.0

Operating pressure = 437.8 kPa
Speed of the lateral = 8.0 $cm.min^{-1}$
Time to complete one revolution = 20.1 h

APPENDIX B

Data for Application Rates

TABLE B-1 APPLICATION RATE DATA AT 183.0-m DISTANCE FROM THE PIVOT

Time Elapsed min	Volume of Water Accumulated mL			
	Observation numbers			
	1	2	3	4
5	3.0	3.0	3.0	3.0
10	10.0	9.0	20.0	24.0
15	50.0	44.0	40.0	44.0
20	60.0	60.0	51.0	64.0
25	91.0	69.0	69.0	95.0
30	92.0	86.0	88.0	105.0
35	121.0	89.0	94.0	107.0

Average application rate = 2.0 $cm.h^{-1}$

Maximum application rate = 4.1 $cm.h^{-1}$

TABLE B-2 APPLICATION RATE DATA AT 152.5-m DISTANCE FROM THE PIVOT

Time Elapsed min	Volume of Water Accumulated mL			
	Observation numbers			
	1	2	3	4
5	8.0	8.0	4.0	2.0
10	12.0	24.5	11.0	11.0
15	27.0	45.0	25.0	18.0
20	39.0	64.0	36.0	30.0
25	550.0	89.0	52.0	45.0
30	69.0	99.0	65.0	56.0
35	73.0	101.0	82.0	69.0
40	74.0	102.0	90.0	87.0

Average application rate = 1.5 $cm.h^{-1}$

Maximum application rate = 2.7 $cm.h^{-1}$

TABLE B-3 APPLICATION RATE DATA AT 122.0-m DISTANCE FROM THE PIVOT

Time Elapsed min	Volume of Water Accumulated mL Observation numbers			
	1	2	3	4
5	3.0	3.0	2.0	2.0
10	14.0	17.0	15.0	10.0
15	42.0	29.0	31.0	29.0
20	47.0	39.0	40.0	45.0
25	51.0	47.0	49.0	49.0
30	55.0	54.0	52.0	76.0
35	62.0	58.0	70.0	90.0
40	70.0	60.0	78.0	92.0
45	75.0	0.0	80.5	0.0

Average application rate = 1.2 $cm.h^{-1}$

Maximum application rate = 3.0 $cm.h^{-1}$

TABLE B-4 APPLICATION RATE DATA AT 91.5-m DISTANCE FROM THE PIVOT

Time Elapsed min	Volume of Water Accumulated mL Observation numbers	
	1	2
10	9.0	10.0
20	21.5	28.0
30	47.5	53.0
40	70.5	82.0
50	96.0	92.0
60	109.0	116.0

Average application rate = 1.3 $cm.h^{-1}$

Maximum application rate = 2.0 $cm.h^{-1}$

TABLE B-5 APPLICATION RATE DATA AT 61.0-m DISTANCE FROM THE PIVOT

Time Elapsed min	Volume of Water Accumulated mL Observation numbers	
	1	2
10	6.0	10.0
20	19.0	18.0
30	56.0	47.5
40	75.0	67.0
50	100.0	94.0
60	141.0	109.0
70	154.0	136.0
80	155.0	144.0

Average application rate = 1.3 $cm.h^{-1}$

Maximum application rate = 2.5 $cm.h^{-1}$

TABLE B-6 APPLICATION RATE DATA AT 30.5-m DISTANCE FROM THE PIVOT

Time Elapsed min	Volume of Water Accumulated mL Observation numbers	
	1	2
10	7.0	5.5
20	15.0	12.0
30	19.0	21.0
40	23.0	30.5
50	34.0	39.0
60	36.0	48.0
70	42.0	49.0
80	55.0	51.0

Average application rate = 0.5 $cm.h^{-1}$

Maximum application rate = 0.8 $cm.h^{-1}$

APPENDIX C

Infiltration Data

TABLE C-1 DATA FOR INFILTRATION TEST 1

Time Elapsed min	Infiltration Rate $cm.h^{-1}$	Depth cm	Moisture Content	
			Initial %	Final %
2	84.0	15	17.53	38.15
5	65.3			
10	11.3	30	9.94	23.32
15	7.2			
20	6.6	45	7.92	22.02
25	4.8			
30	5.1	60	7.50	16.59
35	5.4			
45	6.5			
55	6.6			
65	7.8			

TABLE C-2 DATA FOR INFILTRATION TEST 2

Time Elapsed min	Infiltration Rate $cm.h^{-1}$	Depth cm	Moisture Content	
			Initial %	Final %
2	102.0	15	21.26	25.20
5	15.0			
10	6.6	30	17.16	17.33
15	6.3			
20	6.2	45	13.01	16.69
25	6.0			
35	5.6	60	12.32	13.21
45	4.9			
65	5.9			

TABLE C-3 DATA FOR INFILTRATION TEST 3

Time Elapsed min	Infiltration Rate $cm.h^{-1}$	Depth cm	Moisture Content	
			Initial %	Final %
2	123.0	15	11.58	33.72
5	16.8			
10	12.0	30	8.35	31.28
15	5.4			
20	7.2	45	7.63	18.49
25	6.0			
30	4.8	60	6.33	16.94
40	6.0			
50	5.1			
60	6.6			

TABLE C-4 DATA FOR INFILTRATION TEST 4

Time Elapsed min	Infiltration Rate $cm.h^{-1}$	Depth cm	Moisture Content	
			Initial %	Final %
2	138.0	15	11.06	32.22
5	39.0			
10	21.6	30	8.81	26.4
15	18.0			
20	18.0	45	8.04	18.21
25	18.0			
30	15.0	60	7.4	15.53
40	18.0			
50	16.8			
60	18.6			

TABLE C-5 DATA FOR INFILTRATION TEST 5

Time Elapsed min	Infiltration Rate $cm.h^{-1}$	Depth cm	Moisture Content	
			Initial %	Final %
2	198.0	15	10.83	40.12
5	34.8			
10	9.0	30	8.46	25.72
15	9.0			
20	7.8	45	7.43	21.33
25	7.2			
30	7.2	60	6.65	17.57
40	8.4			
50	7.2			
60	7.8			

TABLE C-6 DATA FOR INFILTRATION TEST 6

Time Elapsed min	Infiltration Rate $cm.h^{-1}$	Depth cm	Moisture Content	
			Initial %	Final %
2	121.5	15	10.5	47.12
5	55.0			
10	16.8	30	7.75	29.87
15	12.6			
20	10.8	45	6.87	22.46
25	12.0			
30	10.2	60	5.38	19.34
40	11.0			
50	10.5			
60	12.3			

TABLE C-7 DATA FOR INFILTRATION TEST 7

Time Elapsed min	Infiltration Rate $cm.h^{-1}$	Depth cm	Moisture Content	
			Initial %	Final %
2	45	15	36.34	
5	40			
10	17.4	30	23.65	
15	7.8			
20	4.8	45	25.28	
25	6.0			
30	6.0	60	17.45	
40	5.1			
50	4.8			
60	6.0			

TABLE C-8 DATA FOR INFILTRATION TEST 8

Time Elapsed min	Infiltration Rate $cm.h^{-1}$	Depth cm	Moisture Content	
			Initial %	Final %
2	126.0	15	18.6	49.2
5	59.0			
10	20.0	30	21.1	40.28
15	16.8			
20	17.4	45	21.7	26.86
25	15.6			
30	13.2	60	16.4	20.32
40	14.7			
50	14.4			
60	13.8			

TABLE C-9 DATA FOR INFILTRATION TEST 9

Time Elapsed min	Infiltration Rate $cm.h^{-1}$	Depth cm	Moisture Content	
			Initial %	Final %
2	231.0	15	8.6	37.2
5	46.0			
10	23.4	30	9.5	35.9
15	19.2			
20	18.0	45	5.0	26.7
25	18.6			
30	19.2	60	7.3	23.0
40	19.5			
50	20.1			
60	20.4			

TABLE C-10 DATA FOR INFILTRATION TEST 10

Time Elapsed min	Infiltration Rate $cm.h^{-1}$	Depth cm	Moisture Content	
			Initial %	Final %
2	171.0	15	13.7	38.0
5	43.0			
10	17.4	30	8.0	22.8
15	12.6			
20	12.0	45	6.2	20.8
25	11.4			
30	11.4	60	5.7	17.3
40	11.7			
50	11.1			
60	11.7			

TABLE C-11 DATA FOR INFILTRATION TEST 11

Time Elapsed min	Infiltration Rate $cm.h^{-1}$	Depth cm	Moisture Content	
			Initial %	Final %
2	150.0	15	12.5	36.34
5	35.0			
10	28.2	30	9.8	23.65
15	24.0			
20	22.2	45	7.7	21.1
25	23.4			
30	22.8	60	7.9	20.6
40	24.3			
50	17.7			
60	22.2			

TABLE C-12 DATA FOR INFILTRATION TEST 12

Time Elapsed min	Infiltration Rate $cm.h^{-1}$	Depth cm	Moisture Content	
			Initial %	Final %
2	45	15	2.1	33.0
5	42			
10	21.6	30	9.4	27.7
15	16.8			
20	14.4	45	8.3	26.4
25	15.0			
30	15.0	60	8.3	23.0
40	14.7			
50	14.1			
60	15.0			

APPENDIX D

Computer Program, FORTRAN

```
$JOB    WATFIV  LATIF,NOEXT
C
C  THIS PROGRAM CALCULATES WEIGHTED & UN-WEIGHTWD CHRISTIANSEN
C  COEFFICIENT OF UNIFORMITY FOR CENTER PIVOT SYSTEMS
C
      REAL ROW1(50),ROW2(50),ROW3(50),ARRAY1(50),ARRAY2(50),
     1   ARRAY(50),SUM/0.0/,DSUM/0.0/,AESDEV(50),ABS,
     2    SUM1/0.0/,SUM2/0.0/,SUM3/0.0/,RATIO(50),RARRAY(50)
      REAL SQDEV(50),DSQSUM/0.0/,DIST(50)
      REAL  RS(50),SUMRS,SUMRDS,DSRS(50),ABSRDS(50),ABSUM
      REAL MEAN,MEAN1,MEAN2,MEAN3,VOL(50),ARRAY3(50)
      REAL DSRS1(50),DSRS2(50),DSRS3(50)
      AREA=87.08
       S=5.0
      PI2S=3.141593*2.0*S
      REAL,NOEXPT
      M=1
      WHILE( M.LE. NOEXPT ) DO
      EXECUTE ARRAY
       SUMRS1=SUMRS2=SUMRS3 =0.0
         SUMRS=SUMRDS=VOLUME=0.0
         I=1
         WHILE ( I .LE. NUM ) DO
         RS(I)=0.5*S+(I-1)*S
         SUMRS=SUMRS+RS(I)
         DSRS(I)=RS(I)* ARRAY(I)
         DSRS1(I)=RS(I)*ARRAY1(I)
         DSRS2(I)=RS(I)*ARRAY2(I)
         DSRS3(I)=RS(I)*ARRAY3(I)
         SUMRS1=SUMRS1+DSRS1(I)
         SUMRS2=SUMRS2+DSRS2(I)
         SUMRS3=SUMRS3+DSRS3(I)
         VOLUME=VOLUME+DSRS(I)*PI2S/100.0
         VOL(I)=VOLUME
         SUMRDS=SUMRDS+DSRS(I)
        I=I+1
         END WHILE
      DPRM=SUMRDS/SUMRS
      DPRM1=SUMRS1/SUMRS
      DPRM2=SUMRS2/SUMRS
      DPRM3=SUMRS3/SUMRS
      MEAN=SUM/N
      MEAN1=SUM1/N
      MEAN2=SUM2/N
      MEAN3=SUM3/N
      ABSUM=0.0
       DSUM=DSQSUM=ABSUM1=ABSUM2=ABSUM3=0.0
```

```
J=1
  WHILE ( J .LE. NUM ) DO
   DIST(J)=S*J
   ABSDEV(J)=ABS(ARRAY(J)-MEAN)
   DSUM=DSUM+ABSDEV(J)
   SQDEV(J)=ABSDEV(J)*ABSDEV(J)
   DSQSUM=DSQSUM+SQDEV(J)
   ABSRDS(J)=RS(J)*ABS( ARRAY(J)-DPRM)
   ABSUM=ABSUM+ABSRDS(J)
   ABSUM1=ABSUM1+RS(J)*ABS( ARRAY1(J)-DPRM1)
   ABSUM2=ABSUM2+RS(J)*ABS( ARRAY2(J)-DPRM2)
   ABSUM3=ABSUM3+RS(J)*ABS( ARRAY3(J)-DPRM3)
   J=J+1
END WHILE
 HCCU=100.0*(1.0-ABSUM/(DPRM*SUMRS))
   CCU=100.0*(1.0-(DSUM/(MEAN*N)))
 HCCU1= 100.*(1.0-ABSUM1/(DPRM1*SUMRS))
     HCCU2= 100.*(1.0-ABSUM2/(DPRM2*SUMRS))
HCCU3=100.*(1.0-ABSUM3/(DPRM3*SUMRS))
 STDEV=SQRT(DSQSUM/N)
STERR=STDEV/SQRT(N+0.0)
I=1
 WHILE ( I .LE. NUM ) DO
   RATIO(I)=ABSDEV(I)/STDEV
   I=I+1
END WHILE
PRINT 100,(DIST(K),ARRAY1(K),ARRAY2(K),ARRAY3(K),
1ARRAY(K),VOL(K),ABSDEV(K),SQDEV(K),RATIO(K),K=1,N)
 PRINT 120,MEAN1,MEAN2,MEAN3,MEAN,DSUM,DSQSUM
 PRINT 130,N,CCU,AREA,STDEV,STERR
 PRINT 115,M
PRINT 125,HCCU1,HCCU2,HCCU3,HCCU,DPRM1,DPRM2,
1         DPRM3,DPRM
PRINT 140, (ROW1(L),ROW 2(I),ROW3(I),L=1,N)
PRINT 150,HCCU,DPRM,ABSUM,(DIST(I),RS(I),DSRS(I),
1        ABSRDS(I),VOL(I),I=1,N)
M=M+1
END WHILE
STOP
REMOTE BLOCK ARRAY
   READ,NUM,(ROW1(J),ROW2(J),ROW3(J),J=1,NUM)
   N=NUM
   SUM=SUM1=SUM2=SUM3=VOLUME=0.0
   I=1
   WHILE ( I .LE. NUM ) DO
   ARRAY1(I)=ROW1(I)/AREA
   ARRAY2(I)=ROW2(I)/AREA
   ARRAY3(I)=ROW3(I)/AREA
```

```
            ARRAY(I)=(ROW1(I)+ROW2(I)+ROW3(I))/(AREA*3.0)
            SUM=SUM+ARRAY(I)
            SUM1=SUM1+ARRAY1(I)
            SUM2=SUM2+ARRAY2(I)
            SUM3=SUM3+ARRAY3(I)
            I=I+1
            END WHILE
          END BLOCK
100       FORMAT('1',T5,'DISTANCE',T20,' ARRAY 1',T38,'ARRAY 2',
         1T55,'ARRAY3',T70,'AVERAGE',T100,'X-MEAN',T110,'SQUARE',
         2T120,'RATIO'/(' ',T2,6(F10.2,5X),T98,3(F6.2,5X)))
115       FORMAT(///T20,'  EXPERIMENT NO =  ',I3////)
120       FORMAT(T15,'MEAN',T17,4(F10.2, 5X),T95,'SUM',T96 ,
         1    2(F10.4,1X)//T15,100('_')//)
  125    FORMAT('0',T30,5HHCCU1,T40,5HHCCU2,T50,5HHCCU3,
         1T60,4HHCCU/T25,4F10.2//T10,14HWEIGHTED MEANS,4F10.2)
130       FORMAT(T20,' NO OF OBSERVATIONS',T45,'UNIFORMITY
         1COEFFICIENT',T70,'X-AREA OF CAN',T90,'ST DEV',T110,
         2 'ST ERR'/T30,I3,T50,F6.2,T75,F8.4,T90,2(F15.4,5X))
 140      FORMAT('1',T30,' DATA READ'//(T20,3(F10.2,5X)))
150       FORMAT('1',T40,4HHCCU,T60,6HDEPTIME,T80,'ABS SUM',T100,
         1'VOLM'/T35,3(F10.2,10X)/T20,4HDIST,T40,2HRS,T60,'RS*DS'
         2,T80,'ABS RDS'/(T16,5(F10.2,10X)))
          END

$ENTRY
```