EFFECT OF DIFFERENT SPRINKLER PATTERNS ON THE PERFORMANCE OF SOLID-SET SPRINKLER IRRIGATION SYSTEM UNDER SHAMBAT CONDITIONS

By

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Dedication

To the soul of my father…

To my kind mother

To my brothers and sisters

To my friends and colleagues

I dedicate this work

Moutasim

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My thanks and praises to the most Gracious and Merciful (Allah) who gave me the strength and patience to conduct this study.

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A	Area
ANOVA	Analysis of variance
ASAE	American Society of Agricultural Engineers
asl	Above sea level
cm	Centimeter
°C	Degree centigrade
Ø	Diameter
FAO	Food and Agriculture Organization of the United Nations
g	Acceleration due to gravity
h	Hour
sec	Second
f	Feddan = 0.42 hectare
mbar	Milli-bar
n	Number of observations
Ns	Number of sprinkler heads
P	Probability (level of significance)
PVC	Poly vinyl chloride
q	Sprinkler discharge
km	Kilometer
VAP	Vapour pressure
RH	Relative humidity
WS	Wind speed
m	Metre

ABSTRACT

A study to design a sprinkler system for small farms and to compare the performance of different sprinkler patterns was carried out at The Demonstration Farm of the Faculty of Agriculture, University of Khartoum at Shambat during March and April 2004. The experiment consisted of testing the effect of square, rectangular and triangular sprinkler patterns on water distribution efficiency (Chirstiansen's coefficient of uniformity 'CU%' and uniformity of distribution 'DU%') and water losses (%) using the completely randomized design (CRD). The effect of some weather factors on pattern efficiency and water losses was also tested using Pearson's coefficient of correlation.

The statistical analysis showed that water distribution efficiency (CU% and DU%) and water losses (%) were not significantly affected by sprinklers pattern ($P \leq 0.05$). However, mean CU% gave the values of: triangular pattern (80.2%), square pattern (79.6%) and rectangular pattern (77.2%), while DU% gave the values of: triangular pattern (69.9%), square pattern (69.1%) and rectangular pattern (66.6%).

The results obtained for water loss mean values were: rectangular pattern (29.4%), square pattern (28.5%) and triangular pattern (26.7%).

As represented by Pearson's coefficient of correlation, wind speed was inversely related to CU%, DU% and water loss% under the three sprinkler patterns.

ملخص الدراسة

أجريت الدراسة لتصميم نظام ري بالرش للمزارع الصغيرة ومقارنة أداء مخططات (أنماط) رش مختلفة في المزرعة التعليمية بكلية الزراعة، جامعة الخرطوم في شمبات خلال شهري مارس وابريل 2004م.

اشتملت التجربة على اختبار أثر مخططات (أنماط) الرش المربع والمستطيل والمثلث على
و انتظام التوزيع CU%كفاءة توزيع مياه الري بالرش (معامل كريتسيانسن للتوزيع
) وفواقد المياه (%) باستخدام التصميم كامل العشوائية. أيضا تم اختبار أثر بعض DU%
عوامل الطقس على كفاءة المخطط (النمط) وفواقد المياه باستخدام معامل بيرسون للارتباط.

أوضح التحليل الاحصائى أن مخططات (أنماط) الرش غير مؤثر معنوياً على كفاءة التوزيع
CU%) وفواقد المياه (عند مستوى المعنوية 5%) وبالتالي متوسط DU% و CU%(
للمخططات (الأنماط) الثلاثة أعطت القيم التالية:المثلث 80.2% والمربع 76.6% والمستطيل
القيم التالية: المثلث 69.9% والمربع 69.1% 77.2%DU% عندما أعطت متوسط
والمستطيل 66.6%.

أوضحت النتائج أن متوسط فاقد المياه للمخططات (الأنماط) الثلاثة هي:المستطيل 29.4% والمربع 28.5% والمثلث 26.7%.

كما هو موضح بمعامل بيرسون للارتباط وجد سرعة الرياح ذات علاقة عكسية مع متوسط
وفاقد المياه (%) تحت مخططات (أنماط الرش الثلاثة).DU% و CU%قيم

CHAPTER ONE

INTRODUCTION

Irrigation in its broad sense is the application of water to the soil for the purpose of supplying moisture essential for plant growth (Israelsen *et al.*, 1962). It has been practiced in many counties in the world for centuries. The importance of irrigation is well known through the history of mankind. Development and utilization of land and water sources constitute problems of major concern to many countries, particularly those dependent on agriculture.

The major constrains to produce more food to meet the increasing demands of the world population is land and water scarcity. One possible approach to conserve these scarce resources may be through introducing efficient irrigation systems. Under the conditions of drought and signs of water shortage, studies of efficient use of water and adoption of modern irrigation techniques such as sprinkler irrigation is gaining more attention in Sudan.

In the early 1900's the pressurized water systems of cities were used to sprinkle lawns and parks, then moved into nurseries and in open fields for producing high value crops. To day sprinklers are seen all over the world on most types of crops.

Sprinkler irrigation is recognized as an adaptable way of supplying most types of crops with frequent and uniforms application of water over a wide range of topographic and soil conditions. The most important advantage of sprinkler irrigation is its flexibility in operation and the highly controlled application of water which makes it best suited to a wide range of soils to be irrigated. On the other hand, major disadvantages of this system are its high initial cost and necessity of using skilled labour.

Sudan is mainly an agricultural country which depends mainly on irrigation. Irrigated agriculture is responsible for a large percentage of the total agricultural production. Irrigated agriculture in the Sudan depends mainly on water from the River Nile and its tributaries. The utilization of the Nile water is subject to the 1959 Nile water agreement between Egypt and Sudan. According to the agreement, Sudan's allotted share is 18.5milliards m^3 (as measured at Aswan) annually. The amount would be able to irrigate about 4 to 4.8 million feddans (Beshir, 1985; Al-araki, 2002), whereas about 200 million feddans is the area of potentially productive land. Thus, in the near future water would constitute a limiting factor in agricultural expansion in the country.

The irrigation method practiced in Sudan is the surface irrigation, which requires much more water to be applied than that actually needed by crops to compensate for water loss through evaporation, seepage, runoff and deep percolation. The over all efficiency of surface irrigation is between 45 to 60 %. Whereas sprinkler irrigation operates at an over all efficiency approaching 75 %.

In many cases the holdings or farms to be irrigated are small, specially around cities and towns. An efficient sprinkler system depends on a good design and factors which affect uniformity and distribution of irrigation water. A major factor affecting irrigation water uniformity of distribution is the arrangement and spacing of nozzles on the lateral and spacing between laterals (pattern adopted). Which means the geometrical water application shapes made by nozzle arrangement on any two adjacent laterals. There are commonly three types of patterns, namely: square, triangular and rectangular. The pattern adopted is believed to affect system efficiency.

Therefore, the design of small farm sprinkler irrigation system under Shambat condition will be investigated in order to achieve the following objectives:

1. Design a sprinkler irrigation system for small farms areas.
2. To compare the performance of different nozzle arrangements (patterns) in order to adopt the best pattern in the design of small farm sprinkler irrigation system.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Irrigation generally is defined as the application of water to the soil for the purpose of supplying moisture essential for plant growth, for the purpose of crop production, to dilute salts in the soil, to provide crop insurance against short duration drought, to cool the soil and atmosphere by making favorable environment for plant growth, to reduce the hazards of soil piping, and to soften tillage pans (Israelsen *et al.*, 1962 and Michael, 1978).

Irrigation water is supplied to supplement the water available from rainfall and contribution to soil moisture from ground water. In many areas of the world, the amount and timing of rainfall are not adequate to meet the moisture requirement of crop and irrigation is essential to raise crops necessary to meet the human need of food and fiber (Michael, 1978).

2.2 Water application methods

According to Israelsen *et al*., (1962) and Michael (1978) irrigation water application is generally accomplished by four different methods. It may be applied to the crop by flooding it on the field surface (surface irrigation), by applying it beneath the soil surface (subsurface irrigation), by applying it in drops (drip or trickle irrigation) or by spraying it under pressure (sprinkler irrigation).

2.2.1 Surface irrigation

In surface methods, irrigation water is applied directly to the soil surface from a channel located at the upper reach of the field. Water may be distributed to the crop in border strips, check basins or furrows (Michael, 1978).

2.2.2 Sub-Surface irrigation

In sub-surface irrigation water is applied below the ground surface by maintaining an artificial water table at some depth depending upon the soil texture and the depth of plant root. Water reaches the plant roots through capillary action. Water may be introduced through open ditches or under ground pipe lines such as tile drains or mole drains or drippers. The water application system consists of supply channels, ditches or trenches and drainage ditches for disposal of excess water (Michael, 1978).

2.2.3 Drip or trickle irrigation

Drip or trickle irrigation is one of the latest methods of irrigation which is becoming increasingly popular in areas with water scarcity and salt problems. It is a method of watering plants frequently and with a volume of water approaching the consumptive use of the plant, thereby, minimizing such conventional losses as deep percolation, run off and soil water evaporation.

In this method, irrigation is accomplished by using small diameter plastic lateral lines with emitters to deliver water near the base of the plant (Michael, 1978).

2.2.4 Sprinkler irrigation

Sprinkler irrigation method was introduced about 1900, and the early development occurred principally in Sacramento valley, California. In this method,, water is applied to the soil surface as a spray simulating rain fall. The spray of water was developed by forcing it through small orifices or nozzles under pressure, which is obtained mainly by pumping or gravitational force if water source is high. The system can be adapted for nearly all crops (rice is an exception), all soils, most topographic conditions and all climates.

Sprinkler system uses pressure energy to from and distribute droplets over the land surface. Although normally designed to supply the irrigation requirement of the farm, sprinkler irrigation systems are also used for crop and soil cooling, frost protection, controlling wind erosion, providing water for germinating seeds and reuse of waste water for agriculture (Israelsen *et al.*, 1962; Michael, 1978 and James 1988).

a) Advantages of sprinkler irrigation

Considering the advantages of sprinkler irrigation in solving problems of irrigation, Israelsen *et al.*, (1962) reported that water measurement is easier with sprinkler than with surface irrigation. With sprinkler less interference is encountered in cultivation and other farm operations. Higher water application efficiency can be obtained by sprinkler irrigation. When water is already pumped to the point of use, the pressure needed for sprinkler can be obtained with minimum additional capital investment, and when domestic and irrigation water comes from the same source, a common distribution line can be frequently used. Sprinkler irrigation can be provided at a lower capital investment per area of irrigated land in case of areas requiring frequent irrigation.

b) Disadvantages of sprinkler irrigation

The major disadvantages of sprinkler irrigation system are stated by Molenaar (1960) as follows:

1. The high initial cost of equipment and high construction cost.
2. Sprinkler irrigation is not well adapted to conditions where water supply is available intermittently.
3. Unless the sprinkler system can be operated almost continuously, the investment in equipment may become so high as to make its use prohibitive.

4. Moving the portable lines when the soil is soft and the crop is wet is an unfavorable task.
5. Mechanical difficulties must be expected. Sprinkler fails to rotate, nozzles may clog, couplers may leak, or the engine may require attention.

2.3 Types of Sprinkler Irrigation Systems

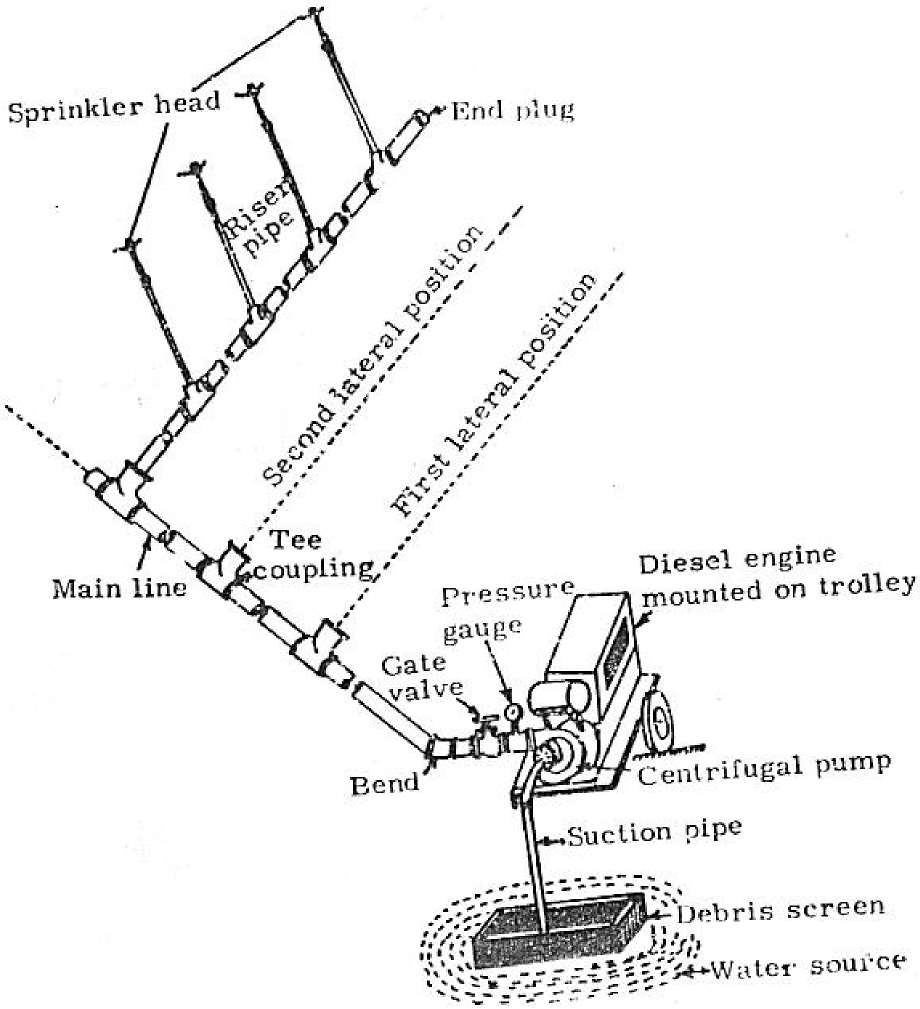
Based on the degree of portability, sprinkler irrigation systems are generally classified as portable, semi-portable, semi-permanent and permanent systems. Sprinkler irrigation systems may also be classified according to special features that are used to move the lateral pipe line (Molenaar, 1960; Michael, 1978; and James, 1988).

2.4 Components of Sprinkler System

The sprinkler systems have the following basic components in common as shown in Fig 2. 1.

The pump draws water from a source, main pipeline which delivers water from the pump to the lateral line, lateral pipe line which delivers water to the sprinklers and the sprinkler heads which are mounted on risers. There are three types of sprinkler heads namely: rotating heads,

Fig. 2.1 Components of Sprinkler Irrigation System



Source: Michael, 1978

spray heads and perforated pipes. The rest of the system components include valves and fittings (Pair, 1960; Michael, 1978 and Kay, 1983).

2.5 Performance of Sprinkler System

Operating pressure and nozzle geometry (i.e. nozzle operating pressure, size, shape and angle) are primary factors affecting system performance. The performance of sprinkler is described by its discharge, distance of throw, distribution pattern, application rate and droplet size.

i. Sprinkler discharge

Sprinkler discharge is the volume of water per unit time passing out of sprinkler nozzle. Sprinkler discharge can be computed from the following formula (Michael, 1978):

$$q = C.A.\sqrt{2gh} \quad .... \quad \mathbf{(2.1)}$$

Where:

q = sprinkler's nozzle discharge (m^3/s).

A = cross-sectional area of the nozzle (m^2).

g = acceleration due to gravity (m/sec^2).

h = pressure head at the nozzle (m).

C= coefficient of discharge which is a function of friction loss (the coefficient of good nozzles can be assumed as (0.95 to 0.96).

Sprinkler discharge is tested by placing a hose over the nozzle and directing the water into a calibrated container. The discharge equals the volume of water divided by the time taken to collect that volume (Criddle *et al.*, 1956; kay, 1983).

Sprinkler manufacturers commonly publish tables of pressure and discharge data for various nozzle diameters. Sprinkler discharge is not related to the nozzle angle.

ii. Distance of throw

The distance of water throw of sprinkler governs the spacing between adjacent sprinklers. Spacing usually increases as the distance of throw is increased. The operating pressure, and the size, shape and angle of the nozzle opening determine the distance a sprinkler throws water. Sprinkler manufacturers commonly publish wetted diameter or other measures of distance of throw for different operating pressures and nozzle sizes, shapes and angles (Al-araki, 2002).

iii. Application rate

Application rate refers to the rate at which sprinklers apply water when a group of them are operating close together. It is measured in unit length per unit time (L/T). It depends on the size of sprinkler nozzle, the operating pressure and the spacing between sprinklers. The application rate should always be less than or equal to the infiltration rate of the soil as this will avoid possible erosion and surface runoff (Kay, 1983).

iv. Droplet size

A sprinkler normally produces a wide range of drop sizes from 0.5mm up to 4.0 mm in diameter. Drops larger than this tend to break up into smaller droplets. The smaller droplets usually fall close to the sprinkler while the larger ones travel much further. Large drops can damage delicate crops and some soil by breaking down the surface structure and reducing the infiltration rate (a process known as soil capping). In such cases, only sprinklers producing small droplets should be used to lessen the damage (Kay, 1983).

Keller (1970) reported that there is rather a conclusive evidence that the application rate and drop distribution have a definite effect on the tilth of medium and fine textured soils. Soil tilth can be destroyed by high application rates specially when coupled with long durations and poor soil drainage.

v. Operating pressure

In order to reduce energy consumption and lower operating cost, sprinkler system should operate at the lowest pressure at which acceptable application uniformity and efficiency can be achieved. Sprinkler manufacturer's catalogues usually identify a recommended range of operating pressure that results in acceptable performance for each sprinkler. The design operating pressure should be as low as possible and within the recommended range.

vi. Water distribution pattern

The rate of water application by a single sprinkler normally varies with distance of throw. It is heavy close to the sprinkler and reduces towards the edge. To make the distribution pattern more uniform, several sprinklers are operated close together so that their distribution overlaps. This determines spacing needed between sprinklers (Makki, 1996 and Al-araki, 2002).

2.6 Factors Affecting Sprinkler Performance

An understanding of factors governing sprinkler performance is necessary to select the best sprinklers to fit the operating conditions. These factors include, nozzles, operating pressure, sprinkler rotation and wind speed and direction.

2.6.1 Sprinkler nozzle

Water distribution varies with sprinkler and nozzle design. Twin nozzle sprinklers apply water more uniformly than single nozzle sprinklers.

2.6.2 Nozzle operating pressure

Sprinkler discharge is a function of the nozzle diameter and the pressure at nozzle. A sprinkler performs best at a given pressure which is normally specified by the manufacturer. Maximum application rates are inversely related to nozzle pressure and wetted diameter.

2.6.3 Sprinkler rotation

Rotation rate of a sprinkler should be uniform for the best water distribution pattern.

2.6.4 Wind speed and direction

According to Kay (1983) spray from sprinklers is easily blown by wind and this distorts water distribution from sprinkler nozzle and upsets the distribution uniformity. To reduce this, sprinkler spacing can be brought closer together. The effect of wind speed on the required spacing of sprinklers is shown in Table 2.1.

2.7 Design of sprinkler irrigation system

Molenaar (1960) indicated that the steps involved in the design of sprinkler system include making an inventory of the available resources on the existing conditions, designing the best suitable layout of the system and finally the actual engineering and hydraulic design. Also Israelsen *et al.*, (1962) reported on the proper sprinkler design which

Table 2.1 Effect of Wind Speed on Sprinkler Spacing

Wind Speed (m/s)	Diameter of Wetted Circle (m)		
	32	37	42
	Sprinkler Spacing (m)		
No wind	21	24	27
0 – 2.5	18	21	24
2.5 – 5.0	15	18	21
Over 5.0	9	12	12

Source: Kay (1983)

should involve careful consideration of soils, topography, crops, water supply, management, consumptive use, hydraulics, labour and power cost. The proper selection of equipment and sprinkler spacing are required in order to achieve the required design.

Schwab *et al*., (1966) concluded that not only should sprinkler system be properly designed hydraulically and economically but also the design should consider the availability of labour for moving the sprinkler pipe lines.

2.7.1 Engineering and hydraulics of sprinkler system design

The hydraulic design of sprinkler system aims at uniform irrigation water coverage. The main hydraulic principles involved in a sprinkler system design are as follows:

2.7.1.1 System capacity requirement

Required system capacity depends on area to be irrigated, depth of irrigation water need to be applied in each irrigation and operation time available. System capacity can be calculated using the following relationship:

$$Q = \frac{A.d}{100\,f.T} \qquad (2.2)$$

Where:

Q= Required system capacity (m^3/h).

A= Aera to be irrigated (m^2).

d = Depth of irrigation water need to be applied in one irrigation (cm).

f =duration of irrigation - irrigation time - (day).

T= Hours of system operation in a day (20-22h).

2.7.1.2 Discharge of sprinkler

The following equation, stated by Molenaar (1960) can be used to compute the average discharge of individual sprinkler:

$$q = I \times \frac{Sl \times Sm}{1000} \qquad (2.3)$$

In which:

Q = Required average discharge of individual sprinkler (m^3/h).

I = Determined rate of application (mm/h).

Sl = Spacing between sprinklers along the lateral line (m).

Sm = Spacing between position of laterals (m).

2.7.1.3 Application rate

Application rate is the main design parameter. For a single sprinkler it may be estimated from the following formula as stated by Michael (1978).

$$I \text{ or } Ra = \frac{q \times 360}{A} \qquad (2.4)$$

Where:

Ra or I = Average water application rate in cm/h.

q = Average rate of discharge at the nozzle in litre/sec.

A= wetted area of the sprinkler in (m^2).

2.7.1.4 Radius of wetted area of sprinkler

The area covered by a rotating sprinkler may be estimated by the following formula as suggested by Michael (1978):

$$R = 1.35\sqrt{dh} \qquad (2.5)$$

Where:

R= Radius of the wetted area covered by sprinkler (m).

d= Diameter of nozzle (mm).

h= pressure head at nozzle (m).

2.7.1.5 Pressure and discharge ratio

The discharge of sprinkler nozzle is proportional to the square root of the pressure at the sprinkler. This can be expressed by the following equation as suggested by Pair *et al*., (1975):

$$q = k\sqrt{p} \qquad (2.6)$$

Where:

q = Sprinkler nozzle discharge (m^3/s).

k = Nozzle discharge coefficient (a function of friction loss).

p = Sprinkler pressure (m).

2.7.2 Design of sprinkler laterals

The design capacity for sprinklers on a lateral is based on the average operating pressure. Where the friction loss (Hf) in the lateral is 20% of the average pressure, the average head (Ha) for design in a sprinkler lateral line can be expressed by the following formula:

$$Ha = H_o + \tfrac{1}{4} Hf \qquad (2.7)$$

Where:

Ha = Average operating head (m).

H_o = Pressure at the Sprinkler at the farthest end (m).

Hf = The pressure loss due to friction (m).

2.7.3 Main line pipe size

The function of main lines and sub-mains is to convey the required amount of water at the desired pressure to all lateral lines. Under maximum pressure the selection should be based on economical conditions.

The pressure head at the main line can be described by the following equation.

$$Hm = Ha + \tfrac{3}{4} Hf \pm \tfrac{3}{4} He + Hr \qquad (2.8)$$

Where:

Hm = Pressure head at the main line (m).

Ha = Average pressure required to operate the sprinkler head (m).

Hf = Pressure loss due to friction (m).

He = Maximum difference in elevation between the first and last sprinklers on the lateral (m).

Hr = The riser height (m).

Main line friction loss of about 3 meters for small systems and 12 meters for large system may be allowed.

2.7.4 Friction loss in pipes

The friction loss in pipe lines can be computed from the following formula.

$$Hf = f\frac{LV^2}{2gD} \qquad (2.9)$$

In which:

Hf = The friction loss in the pipe line (m).

f = The friction factor.

L = The length of the pipe line (m).

V = The velocity of water in the pipe line (m/sec.).

g = The acceleration due to gravity (9.81 m/sec^2).

D = Pipeline diameter (m).

In sprinkler laterals friction loss can also be computed by Hazen-Williams equation as follows:

$$Hf = 1.21\ (l0^{l0} \text{ x } Q^{1.852} \text{ x } L \text{ x } D^{-4.87}) \qquad (2.10)$$

Where:

Hf = Friction loss inside pipe (m).

Q= Discharge of line (L/s).

C= Friction coefficient (values for some material are shown in Table (2.2).

L = Pipe length (m).

D = Pipe inside diameter (mm).

Friction loss (H'_f) in case of multiple outlets (sprinklers) in a line is multiplied by F 'Christiansen correction factor' (less than 1.0) which depends on the number of the outlets to become:

$H'_f = F \times H_f$ (2.11)

Where:

H_f = friction loss in case of no outlets (m).

For all lines one diameter pipe can be used. For minimizing cost more than one diameter pipes may be used.

2.7.5 Pump and Power Unit

In selecting a suitable pump, it is necessary to determine the maximum total head against which the pump is working. This may be determined using the following formula:

$Ht = Hn + Hm + Hj + Hs$ (2.12).

Where:

Ht = Total design head against which the Pump is working (m).

Table 2.2 Friction Factor (C) values for different materials (pipes)

Material	Friction factor (C)
Plastic (diameter 10 cm and above)	150
Plastic (diameter 5.0 – 7.5 cm)	140
Asbestos cement	140
Aluminum (3 ft)	130
Iron (new)	130
Iron (10 years)	100

Source: Pair *et al*., (1975).

Hn = Maximum head required at the main line to operate the sprinklers on the lateral (m).

Hm = Maximum friction loss in the main and the suction lines (m).

Hj = Elevation difference between the pump and the junction of the lateral and the main (m).

Hs = Elevation difference between the pump and the source of water after draw-down (m).

When the total head and rate of pumping are known, the pump may be selected from rating curves or tables furnished by the manufacturer (Michael, 1978).

2.8 Set time

This term refers to the time taken for a sprinkler to complete an irrigation in one position. It depends on the sprinkler application rate and irrigation need. It is given by the following equation:

$$\text{Set time} = \frac{\text{Irrigation need } (L)}{\text{Application rate } (L / T)} \qquad (2.13)$$

2.9 Sprinkler Pattern and Spacing

Different sprinkler spacings result in different uniformities. This is due to the change in the application rate and the area. Sprinklers may be spaced in triangular, rectangular or square arrangements. All of these prove satisfactory when adequate overlap is provided. Square and triangular spacings are more common. Triangular spacing results from staggering sprinklers along alternate lateral lines (Pair, 1960).

Parchomochuk and Stevenson, (1980) found that triangular sprinkler arrangement gave a better uniformity than an equivalent rectangular arrangement.

For a given wind condition, the primary factors affecting uniformity are nozzle type and size, operating pressure and spacing. For a fixed grid system, there are two spacing dimensions, the distance between sprinklers on a lateral and the distance between laterals. Rough rules of thumb for maximum spacing are given in Table 2.3. The spacings are given as a percentage of sprinkler wetted diameter.

Within the range of small to medium sized sprinklers, it is generally more economical to design the system with the largest sprinkler and spacings permissible. So the two factors that often determine sprinkler nozzle size and spacing are the desired uniformity and the infiltration rate of the soil. With high value crops, high uniformity is desirable on fine textured soils, successful design is close spacing (9m x 12m). On coarser textured soils, where lower uniformities are acceptable, wider spacing may be used (Solomon, 1990).

Evans and Sneed, (1996) reported that sprinkler spacing for portable irrigation systems ranges from 12 m x 12m for small sprinklers to greater

Table 2.3 maximum recommended sprinkler spacing as Percent of Wetted Diameter

Wind Conditions	Spacing
Low (0.0 – 7.0 km/h)	60 -65 %
Moderate (7.0 – 14 km/h)	50%
High (more than 14.0 km/h)	30 – 50%

Source: Solomon, (1990).

than 60m x 60m for gun sprinklers. They further reported that spacing may be square, rectangular, or triangular. Spacings are usually 60 percent of sprinkler wetted diameter, but need to be adjusted for wind conditions. Oliphant (1989) stated that with SPACE program, irrigation designers now have the ability to analyze the uniformity of sprinkler design by evaluating different spacing designs with the aid of a computer. Rectangular and triangular spacing of up to 36m between sprinkler heads can be evaluated with the touch of a few keys.

2.10 Water Distribution Uniformity

The water distribution uniformity is an important measure of performance used in the design and evaluation of sprinkler irrigation systems. The water distribution pattern from a sprinkler is tested with sprinkler operating individually under a set of specific conditions.

2.10.1 The coefficient of uniformity

A measurable index of the degree of uniformity obtainable for any size sprinkler operating under given conditions has been adopted and is known as the uniformity coefficient (CU). This uniformity coefficient is affected by pressure-nozzle relations, sprinkler spacing and by wind conditions. The coefficient is computed from field observations of the depth of water caught in open catch containers placed at regular intervals within sprinkler area. Wind speed and direction, humidity, temperature and time of test should be recorded along with nozzle size and operating pressure of sprinkler (Michael, 1978; Solomon, 1979; Kay, 1983 and Wallender and Ohira, 1987).

The coefficient of uniformity (CU) proposed by Christiansen, (1942) is a common quantification of sprinkler application uniformity. The following equation was used to calculate the (CU) values.

$$CU=100(1- d/m) \qquad (2.14a)$$

$$d = 1/n \Sigma |xi - m| \qquad (2.14b)$$

Where:

CU = Christiansen's coefficient of uniformity (percent).

d = The mean deviation of the application rate (mm).

m = The mean application rate (mm).

n = The number of observations.

xi = An individual application rate (mm).

The catch containers (cans) used in testing the uniformity coefficient are normally ordinary tin cans of about one litre capacity. Rain gauges or other containers can be used. However collector can should have suitable dimensions to give a better estimate of the amount of water distributed.

2.10.2 Distribution uniformity (DU%)

Michael, (1978) concluded that not only the application of the right amount of water to the field, but also its uniform distribution over the field is important. Permissible lengths of irrigation runs are controlled to a large extent by the uniformity of water distribution which is possible for a given soil and irrigation management practice. Water distribution uniformity indicates the extent to which water is uniformly distributed along the run.

Sprinkler irrigation distribution uniformity can be computed using the following equation:

$$DU\% = \frac{\text{Average low quarter of water depth received (mm)}}{\text{Average water depth received (mm)}} \times 100$$

Where:

DU = Sprinkler water-distribution uniformity (efficiency).

The concept of water distribution uniformity is the same as the concept of uniformity coefficient (CU) stated by Christiansen, (1942).

2.11 Sprinkler Irrigation Water Losses

Principles and practices for sprinkler irrigation have advanced to the point that water application efficiency is primarily controlled by the amount of evaporation and drift losses. More knowledge about water losses associated with sprinkler irrigation can significantly help towards assessing the overall application efficiency. The efficiency of sprinkler irrigation depends on the losses which take place during and following an irrigation (Yazar, 1984).

Sprinkler irrigation evaporation losses have been the subject of numerous field, laboratory and analytical studies. These losses were not defined in common terms. There were differences in the definition of evaporation and wind drift losses and in the accuracy of experimental techniques. Experimental loss values range from 2 to 40% with many values falling into 10 to 20% range while analytical and laboratory values are in the 1 to 2% range. Losses are approximately proportional to wind velocity and operating pressure, and are inversely proportional to relative humidity of the air and nozzle size. A close relationship between losses and vapour pressure deficit of the air was also obtained (Frost and Schwalen, 1955; Kohl *et al.*, 1978).

Yazar (1984) stated that combined losses from sprinkler system for a given set of operating conditions have been estimated by using the results obtained from experiments. Combined losses ranged from 1.7 to 30.7% of the applied water.

Losses from sprinkler sprays were evaluated by Kraus (1966), Clark and Finely, (1975) and Konda, (1980) and they found that wind velocity and vapour pressure deficit were the most significant factors affecting the evaporation losses during sprinkling.

Konda (1980) reported that evaporation losses were greater near the sprinkler than at the periphery. Evaporation losses were determined by utilizing the catch-can method by Christiansen (1942) and found that losses ranged from 10 to 42%. However, no correlations of losses with climatic variables were reported (Yazar, 1984).

Kohl *et al*., (1987) used a water soluble chemical tracer and potassium chloride to determine evaporation losses and found that measured evaporation losses were less than 1.5% of the discharged water. The maximum evaporation losses of 1.4% occurred with a 29 ºC air temperatures, 60% relative humidity, 6.8 m/s wind velocity and smooth spray plate. The average evaporation loss was 0.8%. The evaporation losses were divided into two components, smooth spray and coarse spray plates. Approximately 60% of the total loss was evaporated from droplets that reached the catch-cans, and 40% could be attributed to droplets that did not reach the soil surface which evaporated or carried away as mist drift.

2.13 Irrigation in Sudan

The cultivable area in Sudan is estimated to be 105 million hectares or 42% of that total area of the country. The cultivated land is 7.6 million hectares which is only 7% of the cultivated area. Only about 3% consists of permanent crops. The remaining area is consisting of annual crops (FAO, 1997).

The irrigated agriculture constitutes more than 10 % of the cultivated area. Productivity under irrigation is relatively high compared with that under rainfall. Water for crops grown under irrigation is applied through different system of surface irrigation (Elbadawi, 2001).

2.14 Sprinkler Irrigation in Sudan:

Konda (1980) reported that overhead irrigation was practiced on limited scale in the tea plantations in southern Sudan. He further reported that there was a wide scope of sprinkler irrigation application in the Sudan as main or supplemental irrigation. Whereas Amin, (1988) reported that sprinkler irrigation should be adapted in both east and west Equatoria in southern Sudan for coffee production.

Makki (1996) stated that sprinkler irrigation is not commonly used in crop production in Khartoum state, except that used by a few individual farmers in Soba and Geraif. The only used system is operated by the Department of Forestry in Soba for forest plant production.

ElBadawi (2001) reported that some centre pivot systems were used at Omduom to produce Lucerne for export by Arab Company. The systems were relatively suitable under Sudan conditions. Also he recommended that such systems can be used efficiently to produce Lucerne if sound management practices are followed.

Ali (2002) reported that sprinkler and drip irrigation are used in a very limited scale. He further reported that some centre pivot and drip systems are under test at Oumdom and west of Omdurman.

CHAPTER THREE

MATERIALS AND METHODS

3.1. Experimental Site and Layout

A study to design a sprinkler system for small farms and to compare the performance of different sprinkling patterns was carried out. The study was conducted during March and April 2004 at the Demonstration Farm of the Faculty of Agriculture, University of Khartoum at Shambat (longitude 32° 32’ E, latitude 15° 40’ N and altitude 380 m asl) on an area of 1300 m^2. The mean air temperature and relative humidity during the study period were 35 °C and 21.5%, respectively. The climatic data during the study period is shown in Appendix 1.

The experiment consisted of testing the effect of square, rectangular and triangular sprinkler patterns on water losses and distribution uniformity (CU% and DU%). Pattern layout spacing was 7.8 x 7.8 m for the square, equilateral triangle of 9 m, and 9 x 7.8 m for the rectangular pattern. The parameters studied included sprinkler discharge and pressure, distance of throw, system pressure and discharge requirements, water losses and distribution efficiency.

Catch cans (14.5 cm high and 10 cm inside diameter) were placed at the centre of grids of 2m x 2m to collect water depths under each pattern as described by Criddle *et al.,* (1956) and Michael (1978). Cans were coated on their inner walls with motor oil (SAE 20 W/40) to reduce evaporation and water adhesion to the can walls.

The completely randomized design (CRD) was adopted to layout the experiment as shown in Fig. 3.1 with 26 replicates (test runs).

3.2. Sprinkler System Components

Plate 3.1 shows a general view of the pump and power unit and system components.

3.2.1 Pump and power unit

A centrifugal pump (50 mm in diameter) was used to provide the sprinkler system with the required pressure. The power unit used to drive this pump was a commercial auto-motor engine (Honda WP20X). The manufacturer's performance table of the pump is shown in Table 3.1.

3.2.2. Main pipeline

A rubber hose (5 cm in diameter and 9 m long) was used as a main pipeline. One end of the line was connected to the pump outlet and the other end was connected to a junction which branched into a sub-main line with two sides to the left and right.

3.2.3. Lateral lines

Two quick coupler aluminum pipelines (5 cm in diameter with 9 m sections) were used as lateral lines. Each lateral line was 43.8 m long.

3.2.4. Risers

Galvanized steel pipes (1.9 cm in diameter and 1 m high) were used as risers. Risers were set on the lateral lines according to the tested pattern in three arrangements, i.e. square, rectangular and triangular. A buffer plot of 9 m x 7.8 m was set between each two adjacent patterns to avoid water application from any pattern to the other as shown in Fig. 3.1.

3.2.5. Sprinkler heads

The sprinkler heads used were Lego 55 part/full circle (single nozzle, Ø = 4mm) as shown in Plate 3.2. The manufacturer's performance tables of the sprinkler head is shown in Table 3.2.

3.2.6. Joints and accessories

A (T) shaped junction (Plate 3.3) was used to connect and branch the main line into a two-sided sub-main. This was done by connecting 3 threaded pieces of PVC pipes (5 cm in diameter and 50 cm long) to a galvanized steel (T) connector. The double sided end of the connector formed the two sided sub-main line, and the main line was connected to the single side of the (T). Lateral lines were connected to the sub-main line using an (L) shaped arrangement with two PVC pipes (with same specifications as used with the T) and a galvanized steel elbow for each lateral line. The connecting points between the hose and PVC pipes were enforced by three clamps at each point to ensure tightness and prevent any leakage that might occur at the operating pressure. At the point of connection between the main line and the (T) junction a pressure gauge and a valve were connected to regulate water flow to the system.

3.3. Sprinkler System Performance

3.3.1. Sprinkler discharge

To determine the rate of discharge of each sprinkler head, a stopwatch, a calibrated container and a rubber hose were used. The rate of discharge was determined by inserting the nozzle into the rubber hose and directing the water to the calibrated container while recording the time taken to fill it (Plate 3.4). The rate of discharge (m^3/h) was then taken to equal the volume of the container (m^3) divided by the time taken to collect that volume (h). This process was repeated three times for each sprinkler head at the operating pressure and the mean discharge of each head was recorded.

3.3.2. Sprinkler pressure

Sprinkler pressure was determined using a pressure gauge (10 bars) provided with a pitot tube. The pitot tube was inserted tightly to fit inside the sprinkler's nozzle and the highest pressure reading was taken from the gauge (Plate 3.5). This process was repeated three times for each head and the average pressure was recorded.

Table 3.1 Manufacturer’s Performance Table of the Water Pump

Item	Description
Water pump model	WP20X
Type	DF1
Connection diameter	50 mm
Delivered volume	600 L/min
Total head	26 m
Power speed	3600 rpm

Table 3.2 Manufacturer’s Performance Table of Lego 55 Sprinkler Head (4mm nozzle)

Pressure (atm)	Discharge (m^3)	Wetted diameter (m)
1.0	0.57	21.0
1.5	0.69	22.0
2.0	0.81	23.0
2.5	0.91	24.0
3.0	0.99	26.0
3.5	1.07	26.5
4.0	1.14	27.0

Fig. 3.1 The Experimental Layout and Catch Cans Grids

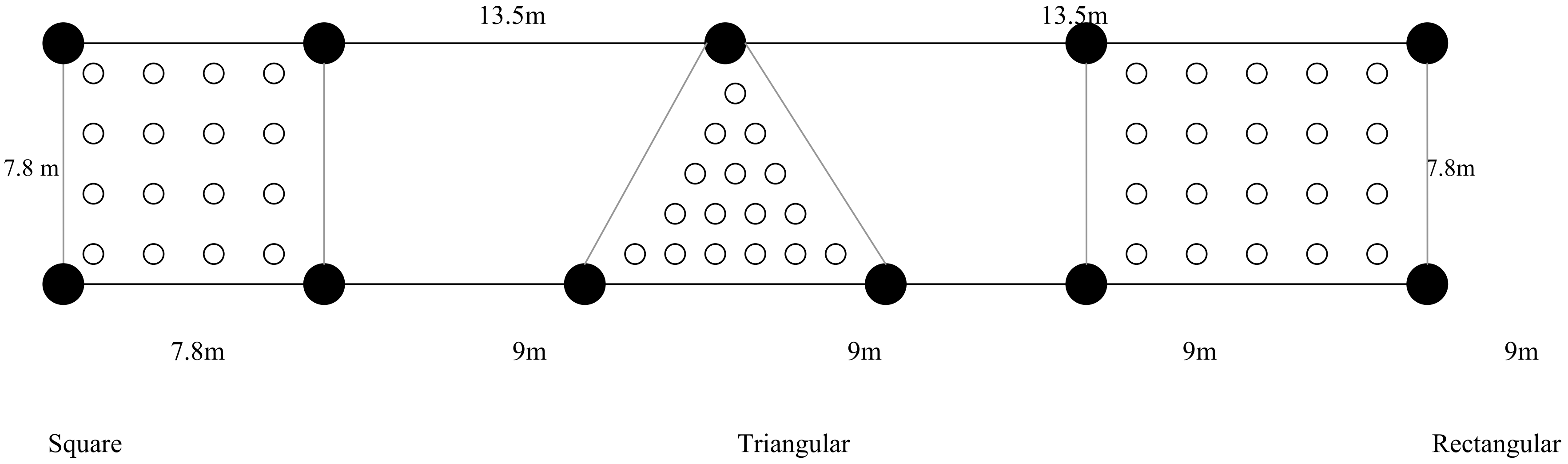


Plate 3.1 General View of the Sprinkler system

Plate 3.2 Lego 55 Sprinkler Head

5 23:18

Plate 3.3 The Main line Junction

3.3.3. Distance of throw

The wetted diameter (distance of throw) of each head was measured from the sprinkler head to the farthest point reached by the sprinkled water using a 30 m long measuring tape. During this process, wind speed and direction, temperature, relative humidity, pan evaporation and vapour pressure were recorded. Wetted diameter was measured at three different angles and the average was recorded for each head.

3.3.4. Water application rate

Water application rate for each pattern was determined using the following equation as stated by Michael (1978):

$$I = \frac{q}{A} \times 100$$

Where:

I = water application rate (cm/h)

q = sprinkler nozzle discharge (m^3/h)

A = Area to be covered (m^2)

3.3.5 Total discharge

The total discharge of the sprinkler irrigation system was calculated by summing the discharge of each sprinkler as follows:

$$Q = Ns \times q$$

Where:

Q = Total discharge of the sprinkler system.

Ns = Number of sprinklers in the system.

q = Individual discharge of the sprinklers (m^3/h).

3.3.6. Water distribution uniformity

a. Christiansen's coefficient of uniformity (CU%)

The pattern uniformity coefficient (CU%) was tested using the following formula as stated by Christiansen (1942):

$$CU\% = 100\left(1 - \frac{\Sigma x}{mn}\right)$$

Where:

CU% = Christiansen coefficient of uniformity (%).

x = deviation of individual observations from the mean value.

n = number of observations.

m = mean value.

b. Distribution uniformity (DU%)

Water distribution uniformity for each sprinkler pattern was determined from the collected depths in the catch cans using the following equation:

$$DU(\%) = \frac{\text{average low quarter of depths collected in the cans (mm)}}{\text{Average water depth collected in all cans (mm)}} \times 100$$

3.4. Water Losses During Sprinkling Process

Water loss was determined for all sprinkling patterns at all test runs. It was taken to equal the difference between application depth of each pattern and the average water depth received in the catch cans. This procedure, however, does not reflect (distinct) the source of water loss whether it is evaporation, or drift. It reflects the total loss during the sprinkling process.

3.5. Data Analysis

The effect of the three sprinkler patterns on water distribution efficiency (CU% and DU%) and water loss was statistically analysed using the analysis of variance tables (ANOVA tables), and the results were presented in tables and figures. On the other hand, the effect of some meteorological factors (wind speed, temperature, relative humidity and vapour pressure) on the patterns efficiencies was tested using Pearson’s coefficient of correlation.

Plate 3.4 Sprinkler Discharge Measurement

Plate 3.5 Sprinkler Pressure Measurement

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Sprinkler Irrigation System

4.1.1 Sprinkler operating parameters

Table 4.1 shows sprinkler discharge (m^3/h), pressure head (m), distance of throw (m) and lateral total discharge (m^3/h). The discharge varied from 0.76 m^3/h for the first sprinkler in the first lateral to 0.70 m^3/h for the distal one with a variation percentage of 7.9%. For the second lateral, it varied from 0.77 m^3/h for the first sprinkler to 0.72 m^3/h for the distal one with a variation percentage of 6.5%. The difference in the variation percentage between the two laterals is attributed to the different numbers of outlets and sprinklers per lateral.

The sprinkler pressure head varied from 20 to 18.3 m for the first lateral and from 20 to 18.8 m for the second one. Pressure variation percentage for the first and second laterals was found to be 8.5 and 6.0%, respectively. The pressure variation percentage for both laterals lied within the range suggested by ASAE (1957) for maximum variation in pressure head for the best performance of sprinkler systems. The sprinkler pressure variation followed the relationship $q/q_o = \sqrt{p/p_o}$. However, this result agreed with the findings of Amin (1988) and Makki

(1996). The good installation and maintenance of the system and good sealing rings used prevented water leakage and hence pressure loss. Therefore, the pressure variation percentage was only due to friction loss and system outlets. The pressure variation percentage is in conformity with that reported by Makki (1996) who reported 7.33% pressure variation using the same lateral line. The comparative difference in the pressure variation percentage can be attributed to the different number of sprinklers used per lateral, spacing between sprinklers along the lateral and types and sizes of sprinkler heads used in the two studies.

The total discharge of the sprinkler system was found to be 8.1 m^3/h, which was 6.5% lower than the rating discharge of the manufacturer's operating table. This can be attributed to the loss in head (pressure) between the different sprinklers in both laterals (average pressure head is 19.1 m).

The distance of throw (m) varied from 12 m to 11.5 m for the first lateral line with a variation percentage of 4.17% and from 12.01 to 11.70 m for the second lateral line with a variation percentage of 3.31%. This variation percentage was due to the variation in the operating pressure as mentioned before. As the pressure increases, water droplets become finer and easily drifted by wind. This trend agreed with the fact that the distance of throw under sprinkler irrigation is proportional to the

Table 4.1 Sprinkler operating parameters

Sprinkler	Lateral No. 1			Lateral No. 2		
	Q $_{(m^3/h)}$	P $_{(m)}$	d $_{(m)}$	Q $_{(m^3/h)}$	P $_{(m)}$	d $_{(m)}$
1	0.76	20.0	12.00	0.77	20.0	12.01
2	0.75	19.1	11.80	0.76	19.6	11.91
3	0.73	18.9	11.73	0.75	19.4	11.85
4	0.72	18.8	11.71	*	*	*
5	0.71	18.4	11.59	0.73	18.9	11.75
6	0.70	18.3	11.50	0.72	18.8	11.70
Mean	0.73	18.9	11.72	0.75	19.3	11.86
Lateral discharge	4.37			3.73		

q = sprinkler discharge (m^3/h).

P = sprinkler pressure head (m).

d = distance of water throw (m).

* = no sprinkler head in this location due to triangular arrangement.

operating pressure as stated by Michael (1978).

4.1.2 Water application rate (Ra)

Water application rate for each sprinkler pattern was found to be 18.3, 19.7 and 22.7 mm/h for the triangular, rectangular and square patterns, respectively. The values show that water application rate (Ra) was higher in the square pattern and this was due to the decrease in the area to be covered. The low Ra under the triangular pattern is probably due to the reduction in the number of sprinkler heads used in that pattern along with the area to be covered and corresponding pressure.

4.2 Sprinkler Water Distribution Efficiency

4.2.1 The effect of sprinkler pattern on Christiansen coefficient of uniformity (CU%)

The values of average CU (%) for each sprinkler pattern were calculated. Table 4.2 shows CU results for the 26 test runs under the three sprinkler patterns, while Fig. 4.1 shows the average CU values under the same patterns. However, catch cans data for the 26 test runs is shown in Appendix 2. From Table 4.2, it can be seen that the minimum and maximum CU values under the triangular pattern were 45.2 and 94.4% at the 10th and 19th test runs, respectively. The minimum CU occurred at 39ºC air temperature, 16% relative humidity and 7.4 km/h wind speed. In contrast, the maximum one occurred at 39.5ºC air temperature, 15% relative humidity and 5.6 km/h wind speed. This shows that the effect of wind speed on CU is quite evident as compared to the effect of temperature and relative humidity.

The minimum and maximum CU values under the square pattern were 58.1% and 92.2% at the 15th and 13th runs, respectively. The minimum CU occurred with 36.5 ºC air temperature, 17% relative humidity and 9.3 km/h wind speed. On the other hand the maximum CU occurred with 37ºC air temperature, 10% relative humidity and 5.6 wind speed. In this regard, the effect of wind speed on CU is well observed.

With the rectangular pattern, the minimum and maximum CU values were 54.2 and 89.4% which occurred at the 5th and 25th test runs, respectively. The minimum CU occurred with 35 ºC air temperature, 15% relative humidity and 9.3 km/h wind speed, whereas the maximum CU occurred at 42 ºC air temperature, 15% relative humidity and 5.6 km/h wind speed.

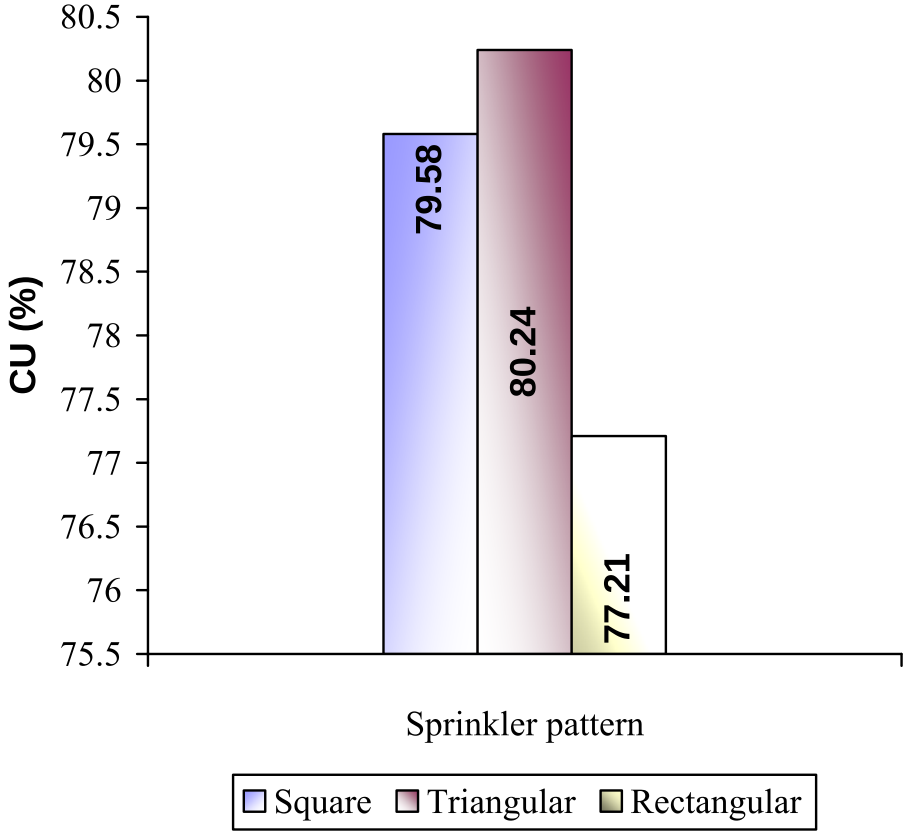
As far as the effect of sprinkler pattern on the mean CU is concerned, Fig. 4.1 shows that the mean values were arranged in the following manner: triangular pattern 80.2%, square pattern 79.6% and rectangular pattern 77.2%. However, the analysis of variance (Appendix 3) did not indicate significant differences ($P \leq 0.05$) between the three sprinkler

Table 4.2 The Effect of Sprinkler Pattern on Christiansen's Coefficient of Uniformity (CU%)

Test run	Christiansen's coefficient of uniformity (%)		
	Square pattern	Rectangular Pattern	Triangular pattern
1	84.07	86.51	88.9
2	81.36	88.94	82.59
3	70.47	71.06	77.17
4	70.76	72.13	80.04
5	78.19	62.10	75.56
6	81.26	54.15	69.63
7	81.38	67.70	55.84
8	84.70	77.64	66.22
9	73.53	65.46	75.21
10	78.15	66.9	45.19
11	71.88	65.21	60.09
12	82.42	83.59	89.96
13	92.24	87.5	94.21
14	76.44	75.45	87.66
15	58.12	68.31	85.79
16	73.41	76.70	85.38
17	82.69	83.49	90.72
18	83.29	84.51	86.35
19	87.48	86.78	94.39
20	74.55	78.80	78.00
21	86.63	89.39	89.65
22	85.43	85.06	90.11
23	79.36	74.95	84.95
24	83.24	81.51	80.34
25	88.34	87.83	89.36
26	79.90	86.33	83.08
Mean§	79.58 ± 0.52	77.21± 0.52	80.24± 0.50

§= means are not significantly different at $P \leq 0.05$.

Fig. 4.1 Average Uniformity Coefficients Under Square, Rectangular and Triangular Sprinkler Patterns



patterns according to Duncan's Multiple Range Test (DMRT). This result is in agreement with that reported by Al-araki (2002) and disagreed with results reported by Parachomchuk and Stevenson (1980). The disagreement with the latter can be attributed to the differences in the nozzle sizes and types of sprinkler heads used, operating pressure and sprinkler spacing. The mean CU under the rectangular pattern (77.2%) is higher than that reported by Amin (1988) and Makki (1996) who reported CU values of 64 and 65%, respectively. This comparatively higher value can possibly be attributed to the narrower sprinkler spacing used in this study as compared to the aforementioned ones.

4.2.2 The effect of weather conditions on CU under the three sprinkler patterns

Table 4.3 shows Pearson's coefficient of correlation between CU and wind speed, temperature, relative humidity and vapour pressure under the triangular, square and rectangular sprinkler patterns. From the Table, it is noted that wind speed at 2m height and relative humidity were inversely related to CU%, while air temperature and vapour pressure are directly related to CU under the three aforementioned patterns. All the relationships between CU and weather conditions under the three sprinkler patterns were found to be weak ($r<0.3$) and insignificant ($P\leq0.05$). This may be attributed to the proper design and close spacing

Table 4.3 The Effect of Weather Conditions on Christiansen's Coefficient of Uniformity Under the Three Sprinkler Patterns

Sprinkler Pattern	WS	T	RH%	VAP
Triangular	- 0.09	0.03	- 0.11	0.14
Square	- 0.25	0.35	- 0.13	0.32
Rectangular	- 0.19	0.31	- 0.12	0.19

WS = wind speed (km/h) at 2 m height.

T = air temperature ºC.

RH% = relative humidity.

VAP = vapour pressure (mbar).

used.

4.2.3 The effect of sprinkler pattern on distribution uniformity (DU%)

Table 4.4 shows the values of distribution uniformity (DU%) under each sprinkler pattern. From the Table, the minimum and maximum DU% under the triangular pattern were 35.3% and 90.4% at the 10th and 19th test runs, respectively. The minimum DU occurred with 10% relative humidity, 39 ºC air temperature and 7.4 km/h wind speed, whereas the maximum one occurred with 15% relative humidity, 39.5 ºC air temperature and 5.6 km/h wind speed. This shows that the maximum and minimum DU% under this pattern followed the same trend of CU%.

Under the square pattern, the minimum and maximum DU% were 54.9% and 87.9% at the 12th and 13th test runs, respectively. The minimum DU% occurred at 10% relative humidity, 35 ºC air temperature and 9.25 km/h wind speed. On the other hand the maximum DU% occurred at 10% relative humidity, 37 ºC air temperature and 5.6 km/h wind speed.

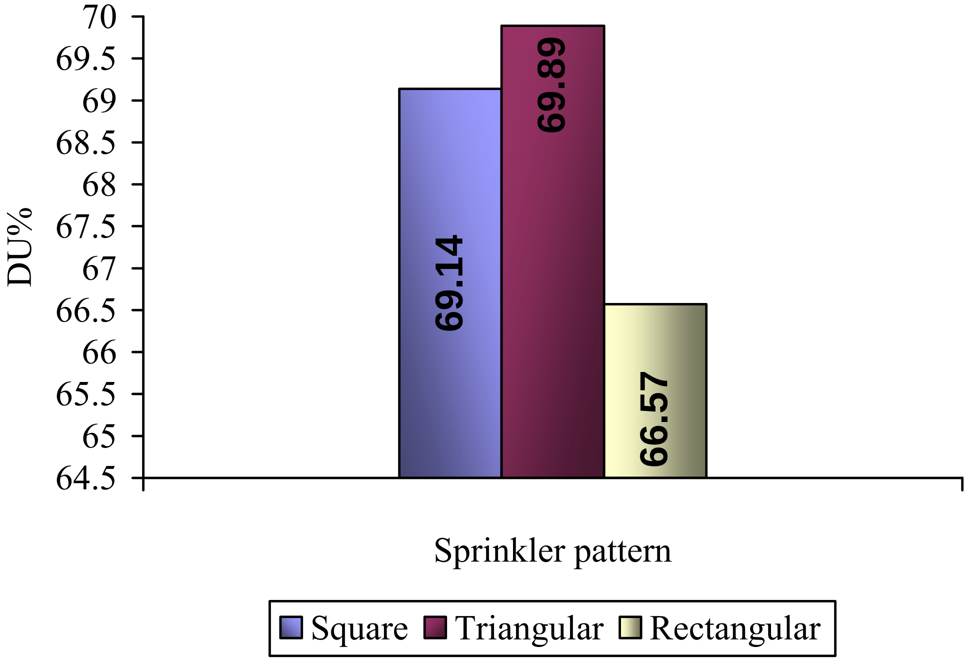
The minimum and maximum DU% under the rectangular pattern were 41.5% and 83.9% at the 11th and 2nd test runs, respectively. The minimum DU% occurred at 10% relative humidity, 35 ºC air temperature and 9.25 km/h wind speed, while the maximum value occurred at 15% relative humidity, 33.5 ºC air temperature and 5.6 km/h wind speed.

Table 4.4 The Effect of Sprinkler Pattern on Distribution Uniformity (DU%)

Test Run	DU (%)		
	Square pattern	Rectangular pattern	Triangular pattern
1	74.29	80.94	82.31
2	69.80	83.90	72.25
3	66.71	52.77	60.61
4	60.32	53.39	66.36
5	69.05	53.39	61.72
6	74.87	44.13	64.99
7	72.25	53.80	43.52
8	74.51	73.35	60.02
9	56.73	47.61	55.57
10	63.09	45.24	35.33
11	54.89	41.52	38.59
12	67.42	74.16	80.79
13	87.53	76.26	88.52
14	63.13	66.43	80.31
15	55.16	56.50	77.69
16	59.25	61.31	75.94
17	68.51	72.68	82.26
18	71.85	74.75	75.03
19	77.25	75.98	90.38
20	60.90	70.60	60.08
21	79.20	80.45	82.57
22	75.01	77.15	82.84
23	65.66	67.19	74.68
24	75.57	77.73	62.19
25	80.88	80.69	85.69
26	73.83	79.69	76.92
Mean§	69.14±0.61	66.57±0.61	69.89±0.60

§= means are not significantly different at $P \leq 0.05$.

Fig. 4.2 Average Distribution Uniformity (DU%) Under Square, Rectangular and Triangular Sprinkler Patterns



The average values of DU% under the three patterns are shown in Fig. 4.3. From the figure, the mean DU% values were arranged in the following manner: triangular pattern (69.9%), square pattern (69.1%) and rectangular pattern (66.6%). However, the analysis of variance (Appendix 3) did not indicate any significant differences ($P \leq 0.05$) between the three patterns according to Duncan's Multiple Range Test (DMRT). These results were in agreement with those reported by Al-araki (2002) and disagreed with the results reported by Parachomchuk and Stevenson (1980). The disagreement can be attributed to the narrower spacing used in this study.

4.2.4 The effect of weather conditions on distribution uniformity (DU%) under the different sprinkler patterns

Table 4.5 shows Pearson's coefficient of correlation between DU% and wind speed at 2m height, air temperature, relative humidity and vapour pressure. Under the three sprinkler patterns, wind speed at 2 m height and relative humidity of the air were inversely related to DU%, while temperature and vapour pressure were directly related to DU%. However, the relationships were weak ($r<0.3$) and insignificant ($P \leq 0.05$). Generally most of the maximum CU% and DU% occurred at low wind speed (5.6 km/h), while most of the minimum values occurred at high wind speed (9.25 km/h).

Table 4.5 The Effect of Weather Conditions on Distribution Uniformity (DU%) Under the Three Sprinkler Patterns

Sprinkler Pattern	WS	T	RH%	VAP
Triangular	- 0.14	0.04	- 0.11	0.12
Square	- 0.20	0.37	- 0.17	0.24
Rectangular	- 0.10	0.28	- 0.35	0.25

WS = wind speed (km/h) at 2 m height.

T = air temperature ºC.

RH% = relative humidity.

VAP = vapour pressure (mbar).

On the other hand air temperature did not have a substantial effect on water distribution under the three sprinkler patterns.The association between water distribution and wind speed and relative humidity was also reported by Solomon (1990) and Makki (1996).

4.3 Sprinkler Water Losses (%)

4.3.1 The effect of sprinkler pattern on water losses (%)

Sprinkler water losses under the triangular, square and rectangular patterns during the 26 test runs are shown in Table 4.6, while the average water losses values are shown in Fig. 4.4. However, sprinkler water losses referred to in this study are not defined in the common terms; either evaporation, or wind drift losses. It represents the total losses which is the difference between the applied depth and the depth caught in the catch-cans. From the Table it can be seen that the highest value of water losses under the square pattern was 62.2% at the 15th test run, with 9.25 km/h wind speed, 4.5 mbar vapour pressure, 14% relative humidity and 35.6 ºC air temperature. The lowest water loss value under this pattern was 0.3% which occurred at the 3rd test run with 7.4 km/h wind speed, 8.8 mbar vapour pressure, 15% relative humidity and 31 ºC air temperature. However, most of the losses values ranged between 26.4 and 49.5 %. Increasing vapour pressure in the air will decrease the evaporation. However the general trend of this result agreed with the results reported by Yazar (1984), and disagreed with what was reported by Kohl *et al,*. (1987). The disagreement with the latter is probably due to the method used to determine water losses and different experimental conditions.

For the rectangular pattern the highest value of water loss of 51.6% occurred at the 21st test run with 7.4 km/h wind speed, 8 mbar vapour pressure, 22% relative humidity and 26 ºC air temperature. On the other hand, the lowest value of 2.5% occurred at the 5th test run with 5.60 km/h wind speed, 7.8 mbar vapour pressure, 14% relative humidity and ºC air temperature. Most of the losses values ranged between 27% and 48.4%, which followed a similar trend to that reported by Yazar (1984).

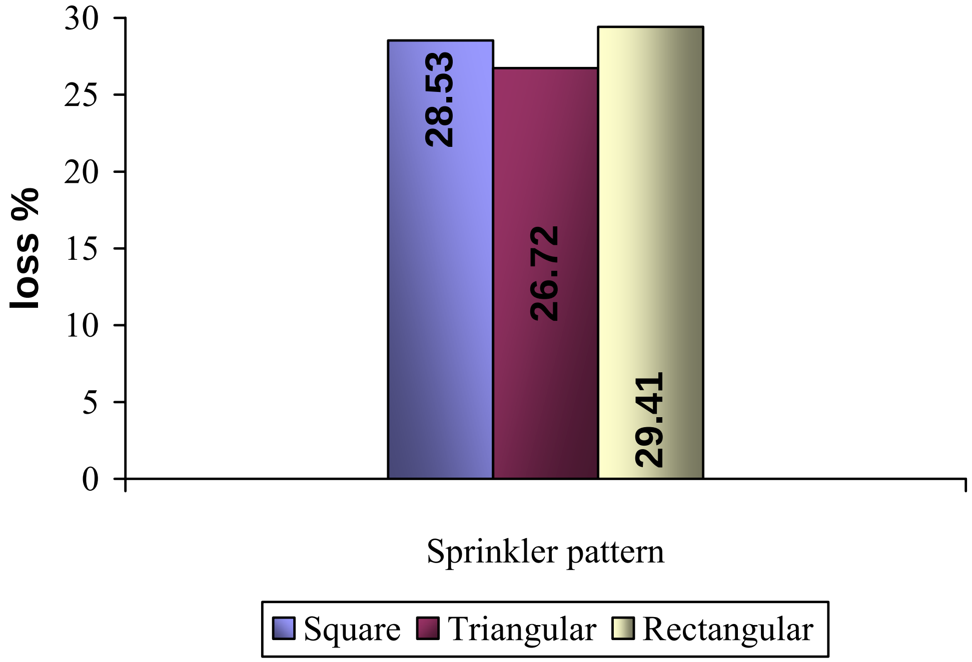
For the triangular pattern, the highest value of water loss was 42.8% at the 15th test run with 9.25 km/h wind speed, 4.5 mbar vapour pressure, 14% relative humidity and ºC air temperature. The lowest loss value (2.5%) occurred at the 5th test run with 5.60 km/h wind speed, 7.8 mbar vapour pressure, 14% relative humidity and 35 ºC air temperature. Most of these values ranged between 20.5 and 42.8%. These results are in conformity with those reported by Yazar (1984).

Table 4.6 The Effect of Sprinkler Pattern on Water Loss (%)

	Sprinkler pattern		
Test Run	Square pattern	Rectangular pattern	Triangular pattern
1	5.55	3.50	5.76
2	10.32	8.91	20.52
3	0.28	8.68	5.16
4	17.41	26.98	36.50
5	3.14	2.50	2.50
6	3.09	4.90	40.15
7	30.07	33.07	38.82
8	12.04	14.71	28.63
9	1.79	5.32	3.98
10	11.02	10.11	3.65
11	12.04	31.68	3.45
12	41.30	51.62	38.53
13	29.93	33.59	20.55
14	24.63	37.02	21.73
15	62.60	48.42	42.78
16	49.54	48.03	37.57
17	44.28	45.47	35.40
18	44.53	47.15	31.49
19	38.77	40.00	26.41
20	46.07	40.74	34.97
21	40.46	36.40	33.75
22	36.95	33.68	35.23
23	49.12	42.36	41.87
24	36.67	36.01	34.10
25	45.69	40.13	39.00
26	44.49	33.68	32.27
Mean §	28.53±17.87	29.41±16.18	26.72±13.97

§= means are not significantly different at $P \leq 0.05$.

Fig. 4.3 Average Water Loss (%) Under Square, Rectangular and Triangular Sprinkler Patterns



The mean water loss values can be arranged numerically in the following manner: rectangular pattern (29.4%)> square pattern (28.5%) > triangular pattern (26.7%) as shown in Fig. 4.3. The statistical analysis did not indicate any significant differences between the three sprinkler patterns in this regard ($P \leq 0.05$).

4.3.2. The effect of weather conditions on water loss (%) under the triangular, square and rectangular sprinkler patterns

Pearson’s coefficients of correlation between water loss (%) and weather conditions under the three sprinkler patterns are shown in Table 4.7. Wind speed at 2m height was inversely related to water loss (r= - 0.3) under the three sprinkler patterns. However, this relationship was shown to be significant under both the square and rectangular patterns, and insignificant under the triangular pattern ($P \leq 0.05$). The Table also shows a direct-weak relationship between temperature and water loss. As far as the effect of vapour pressure and relative humidity was concerned, the same trend of relationship between temperature and water loss was observed under the three sprinkler patterns.

Table 4.7 The Effect of Weather Conditions on Water loss (%) Under the Three Sprinkler Patterns

Sprinkler Pattern	WS	T	RH%	VAP
Triangular	- 0.30	0.18	0.15	0.19
Square	- 0.43*	0.31	0.05	0.15
Rectangular	- 0.50**	0.22	- 0.06	0.01

WS = wind speed (km/h) at 2 m height.

T = air temperature ºC.

RH% = relative humidity.

VAP = vapour pressure (mbar).

*, ** = correlation is significant at P≤0.05 and P≤0.01, respectively.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

From the results of this study, the following conclusions can be drawn:

1. Sprinkler system with a suitable pattern can be designed to irrigate small farms.
2. Water distribution uniformity values (CU% and DU%) under sprinkler patterns was arranged in the following manner: triangular> square> rectangular patterns; despite the insignificant differences between the three patterns.
3. Most of the high CU% and DU% values occurred at the lower wind speed (5.6 km/h), while most of the low ones occurred at moderate to high wind speeds (7.4 – 12.9 km/h).
4. Wind speed and relative humidity of the air were inversely related to the water distribution efficiency (CU% and DU%), while air temperature and vapour pressure were directly related.
5. Average water losses during the sprinkling process were arranged in the following manner: rectangular> square> triangular; despite the insignificant difference between the patterns.
6. Water losses were directly related to wind speed under the three sprinkling patterns. Vapour pressure and relative humidity were inversely related to water losses under the rectangular pattern,

while both weather parameters were directly related to water losses under the square and triangular patterns. Temperature was directly related to water loss under the three patterns.

5.2 Recommendations

Based on the results obtained and conclusions drawn from this study, the following recommendations can be made:

1. Sprinkler system should be adopted to irrigate small holdings.
2. Sprinkler systems should be operated at low wind speed and at the cooler parts of the day.
3. A detailed study on the effect of sprinkler size, operating pressure and spacing on CU% and DU% under different layout patterns is needed.
4. A modeling trial to relate CU%, DU% and water losses to different sprinkling pattern and weather conditions at different combinations of pressure and spacing of a large farm under Shambat conditions is essential.

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APPENDICES

Appendix 1 Air Temperature, Relative Humidity (%), Vapour Pressure (mbar) and Wind Speed During the 26 Test Runs

Run	Weather conditions			
	VAP	RH	TEMP	WS
1	8.5	20	30	12.95
2	7.9	15	33.5	12.95
3	8.8	19	31	9.25
4	8.3	17	33	11.1
5	7.8	14	35	9.25
6	8.7	15	35	12.95
7	12.3	23	34.5	7.4
8	12.3	21	36	7.4
9	12.3	19	37.5	7.4
10	11.2	16	39	7.4
11	5.7	10	35	9.25
12	4.2	7	37	7.4
13	6.2	10	37	5.6
14	8	22	26	7.4
15	4.5	14	36.5	9.25
16	9.1	21	30.5	9.25
17	9.8	14	37.5	7.4
18	10.5	13	41.7	7.4
19	10.4	15	39.5	5.6
20	14.7	23	37.5	7.4
21	13.4	18	40	7.4
22	11.6	17	38.5	5.6
23	12.7	33	28.5	7.4
24	12.5	15	42	9.25
25	12.5	15	42	5.6
26	12.7	15	41	8.32

Appendix 2a Catch Cans Collected Depths (mm) During the 26 Test Runs Under the Square Pattern

Can Number	Test Runs												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	18.7	17.8	27.0	18.7	16.7	16.6	18.2	14.6	11.7	14.0	18.3	27.4	15.3
2	24.7	18.8	27.6	25.5	16.6	17.6	17.6	15.3	13.5	17.6	17.6	13.8	15.5
3	28.8	18.6	20.4	26.7	14.3	15.3	14.0	20.4	10.9	12.5	11.1	14.5	15.2
4	26.7	13.2	16.9	14.9	27.1	22.4	10.2	13.0	19.9	22.8	16.2	6.4	15.3
5	25.0	22.9	32.3	16.9	33.7	23.9	12.7	21.6	25.5	25.2	26.6	7.3	15.5
6	25.8	24.1	34.4	25.5	30.0	25.1	14.9	23.6	26.4	18.3	23.4	13.8	16.8
7	24.8	20.6	25.5	26.7	32.7	30.2	18.7	24.8	30.3	24.1	27.2	14.0	16.4
8	21.4	13.8	17.2	21.3	19.1	27.0	20.5	16.6	28.5	23.2	18.8	10.9	16.9
9	19.7	27.9	33.1	15.9	29.8	17.7	19.0	19.1	28.1	26.4	25.5	12.5	15.3
10	20.8	26.2	31.8	24.4	30.8	25.5	20.4	24.2	25.1	26.4	24.7	14.0	16.8
11	21.4	21.5	17.2	24.8	18.3	26.7	15.8	23.6	36.2	26.1	28.4	14.5	16.9
12	21.3	12.7	14.0	10.4	22.2	26.7	16.8	18.8	18.2	13.8	12.2	13.1	17.2
13	15.9	27.2	16.6	12.7	24.2	16.4	11.2	21.6	21.5	20.0	14.1	13.1	18.1
14	14.0	21.6	18.1	10.8	21.8	19.6	12.1	24.2	25.3	22.7	24.6	13.2	17.8
15	17.2	21.3	15.5	13.1	22.3	18.0	19.4	17.8	20.9	19.4	24.1	13.2	15.2
16	16.6	17.1	14.3	11.2	21.8	23.0	12.4	20.0	14.4	10.7	6.4	11.3	10.1

Appendix 2 a (continued)

Can Number	Test Runs												
	14	15	16	17	18	19	20	21	22	23	24	25	26
1	14.3	17.8	12.4	13.1	12.9	14.3	18.8	11.6	17.7	12.0	13.5	10.4	8.1
2	14.3	16.0	12.1	13.6	14.5	14.4	19.4	14.6	16.0	11.5	13.6	12.5	9.2
3	12.6	11.5	8.5	12.1	13.9	14.9	13.4	15.3	16.8	8.9	13.2	15.0	9.7
4	19.1	7.4	6.0	11.6	9.2	15.2	10.1	15.0	15.5	7.4	11.8	14.1	10.7
5	19.1	6.6	18.6	16.2	9.7	14.5	7.1	14.0	14.3	7.9	11.2	13.1	12.7
6	18.8	9.7	14.6	14.6	14.6	16.7	13.4	16.0	15.8	11.5	15.8	13.2	14.3
7	24.2	12.2	12.5	13.2	14.6	15.3	16.0	15.4	17.6	15.3	18.1	15.3	12.7
8	25.2	12.1	7.0	8.0	14.8	15.0	16.8	11.3	16.0	14.5	16.7	12.5	11.2
9	20.1	5.1	7.0	16.3	13.5	15.3	10.6	13.8	14.8	15.8	19.2	12.2	17.3
10	19.9	5.6	11.1	16.9	15.5	16.2	12.7	14.5	14.5	14.6	18.1	13.5	17.3
11	22.5	7.1	14.5	12.7	13.9	15.0	10.8	13.6	14.9	11.2	15.2	13.1	13.8
12	9.4	5.9	16.9	8.0	8.4	11.7	11.8	17.2	12.0	7.6	10.8	12.0	10.7
13	16.9	5.1	13.9	14.0	13.8	9.0	8.0	9.4	11.5	7.4	9.5	10.7	10.7
14	15.9	4.8	11.8	13.1	13.2	10.6	12.1	10.7	10.6	11.5	12.0	9.9	18.1
15	12.1	5.1	9.0	10.3	9.9	12.6	7.6	11.3	9.9	12.5	14.3	9.2	14.8
16	9.0	3.7	7.1	8.3	8.9	11.6	7.0	12.2	10.9	15.2	16.8	10.3	10.2

Appendix 2b Catch Cans Collected Depths (mm) During the 26 Test Runs Under the Triangular Pattern

Can Number	Test Run												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	16.9	15.0	25.5	11.5	11.1	6.5	14.0	8.9	6.4	8.7	7.1	4.8	8.9
2	18.1	14.0	28.0	14.3	12.4	7.8	15.2	10.8	31.4	19.9	23.8	12.0	15.3
3	15.3	11.6	23.9	12.1	17.1	8.3	15.4	17.2	26.0	20.8	19.6	10.8	16.3
4	14.9	8.0	17.6	11.1	18.8	15.5	15.3	7.6	18.1	42.3	13.9	9.9	14.6
5	13.0	12.1	23.7	7.9	25.0	13.1	15.5	9.7	20.6	70.0	40.5	12.5	15.7
6	21.0	18.6	26.7	15.5	15.5	11.8	16.6	15.9	18.6	24.8	32.3	13.6	15.7
7	18.1	16.3	26.1	15.3	25.2	8.4	16.3	17.8	23.9	19.6	22.4	13.1	15.2
8	18.1	12.0	24.8	13.9	16.3	7.3	5.0	10.8	18.8	39.5	18.2	10.9	14.6
9	18.8	18.8	21.1	12.7	22.4	7.6	4.6	10.2	20.9	47.0	9.8	10.8	15.0
10	17.6	17.6	17.2	10.2	24.2	12.5	5.1	7.0	10.2	14.5	25.0	11.5	15.3
11	20.8	16.3	15.3	10.2	16.9	15.9	5.6	16.8	17.3	13.6	24.7	12.0	14.0
12	14.8	14.5	6.4	5.1	9.7	16.9	6.1	24.2	15.0	6.6	21.3	12.2	14.4
13	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	15.7	12.0	14.5
14	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	13.4	11.3	14.3
15	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	8.5	11.8	14.6
16	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	3.4	10.9	14.6

Appendix 2 b (continued)

Can Number	Test Run												
	14	15	16	17	18	19	20	21	22	23	24	25	26
1	7.1	6.9	6.1	6.0	6.9	12.1	15.4	9.8	8.4	6.1	7.1	9.2	12.7
2	13.9	10.9	12.6	12.1	10.8	15.5	12.5	10.9	9.9	8.1	7.4	10.3	14.3
3	14.0	11.5	12.7	12.4	13.4	13.6	14.6	11.8	10.9	8.7	7.6	10.7	14.8
4	14.0	12.0	12.4	12.6	13.5	11.6	18.6	12.1	11.5	8.9	7.9	10.4	13.8
5	18.2	9.2	14.9	11.8	12.7	13.4	13.6	14.4	12.5	9.3	11.5	11.3	15.3
6	17.7	9.4	13.6	11.8	14.8	13.9	15.0	14.0	13.0	10.9	12.0	13.0	14.8
7	15.8	9.3	12.5	12.9	13.0	14.4	13.2	13.6	12.6	12.0	13.5	12.5	15.8
8	15.3	12.2	10.9	13.9	12.5	14.6	10.2	12.6	11.5	11.2	14.5	11.7	14.8
9	15.8	12.4	10.8	13.9	11.5	14.0	6.4	8.8	12.2	10.9	13.9	11.1	11.7
10	15.5	12.2	13.4	10.6	14.6	13.9	6.0	10.6	13.2	10.2	12.4	10.4	10.2
11	16.3	12.2	12.1	10.9	8.9	12.6	6.4	10.9	13.2	12.9	14.0	13.4	11.2
12	13.5	12.0	12.2	11.5	14.5	13.1	9.9	12.1	13.5	12.4	15.3	12.0	10.7
13	13.5	10.9	9.5	11.5	14.5	13.1	11.7	12.5	13.5	14.0	16.0	12.7	10.7
14	13.2	10.2	10.2	12.6	15.0	13.6	12.2	12.4	12.5	12.0	14.8	11.3	10.2
15	12.5	8.7	9.3	12.4	13.2	13.9	12.2	13.9	11.5	12.5	13.4	9.7	9.2
16	13.2	7.9	9.8	12.7	11.1	12.5	12.7	13.9	10.1	10.4	12.1	9.2	8.7

Appendix 2c Catch Cans Collected Depths (mm) During the 26 Test Runs Under the Rectangular Pattern

Can Number	Test Run												
	1	2	3	4	5	6	7	8	9	10	11	12	13
1	17.4	14.8	22.7	19.1	21.5	23.9	20.4	14.0	7.6	18.0	21.9	9.5	13.2
2	18.6	20.4	21.6	17.2	22.3	9.5	18.2	13.4	15.8	10.3	15.4	9.9	15.3
3	15.3	22.5	18.5	13.8	13.8	6.4	18.8	12.5	10.8	6.6	9.8	7.6	13.4
4	17.6	20.9	18.0	13.2	8.5	6.4	9.7	11.5	5.1	6.1	6.2	6.5	10.2
5	17.2	20.5	18.2	14.0	9.7	9.0	20.6	12.7	12.0	12.7	6.1	7.4	10.2
6	23.6	20.0	29.8	17.2	33.7	40.5	19.9	20.9	22.5	24.6	23.9	11.5	15.2
7	22.4	21.0	31.3	24.8	31.1	43.5	17.7	17.8	19.4	24.7	18.0	12.2	15.0
8	19.5	19.9	21.1	19.1	16.4	9.9	11.2	14.3	17.3	23.2	14.5	10.2	13.8
9	17.4	13.6	17.2	13.9	14.8	12.7	9.8	14.4	18.8	22.4	11.6	7.3	12.2
10	20.5	16.8	18.7	14.5	16.9	22.3	12.4	19.1	14.1	14.8	9.2	6.9	8.9
11	25.0	15.3	24.1	19.7	34.1	21.8	17.4	21.5	27.9	25.0	21.5	12.0	14.6
12	23.2	16.6	25.5	22.3	32.7	33.4	13.0	22.3	27.0	24.7	17.2	11.8	14.8
13	16.0	17.1	17.8	15.3	24.1	15.9	9.4	16.6	32.2	25.0	16.4	11.2	14.6
14	15.0	17.1	12.1	8.9	18.0	11.5	10.8	14.4	26.4	27.6	14.9	8.7	13.8
15	19.9	17.8	11.2	7.6	27.2	31.1	8.1	26.1	9.9	7.3	3.6	7.3	10.3
16	22.0	17.3	12.6	10.8	22.0	15.0	6.7	22.9	18.3	17.7	14.5	11.2	14.8
17	20.4	16.3	14.5	13.4	30.4	18.8	4.1	21.0	26.2	19.2	15.3	10.8	14.3
18	15.9	17.7	12.7	11.3	21.3	15.0	7.0	15.3	30.6	18.6	14.4	9.8	13.1
19	14.5	15.2	6.4	3.8	18.3	13.2	13.8	13.4	19.5	15.4	11.5	8.9	13.4
20	18.1	17.6	5.1	7.1	20.0	14.0	14.1	11.5	10.8	9.7	2.8	9.5	10.2

Appendix 2 c (continued)

Can Number	Test Run												
	14	15	16	17	18	19	20	21	22	23	24	25	26
1	12.1	3.6	10.4	9.8	11.5	12.6	16.0	12.5	12.7	7.4	9.8	18.1	10.2
2	12.0	25.3	9.2	10.7	11.1	12.7	12.4	12.1	12.5	8.9	10.2	11.2	11.7
3	9.7	6.9	7.1	12.4	9.0	10.6	9.8	12.4	15.2	8.4	9.4	11.3	12.2
4	6.6	5.1	4.6	6.1	7.8	9.0	9.5	12.5	13.5	10.4	9.7	11.1	11.2
5	7.8	5.5	6.2	6.4	7.4	8.1	10.6	13.5	14.6	7.5	10.1	11.2	13.8
6	18.0	16.9	14.0	12.5	13.1	7.8	10.8	14.1	15.2	12.9	13.1	12.5	13.2
7	15.5	14.3	11.3	13.0	11.6	9.9	14.1	14.3	16.0	14.6	14.6	13.2	15.8
8	9.2	9.5	9.0	11.8	10.9	12.4	16.6	12.7	15.4	12.2	12.6	12.1	15.3
9	8.5	7.6	8.4	8.3	7.9	13.9	12.7	12.7	12.0	17.1	16.2	12.5	12.2
10	9.3	8.0	11.1	8.8	7.1	14.0	13.5	15.2	15.5	15.2	16.0	13.4	11.2
11	18.2	13.2	14.9	14.0	12.9	13.6	15.0	14.0	16.6	14.5	16.0	13.1	14.8
12	16.2	10.4	12.2	13.5	12.0	13.5	8.4	12.2	13.2	7.3	11.1	10.7	15.3
13	12.6	9.4	5.2	11.5	12.1	13.4	8.3	9.4	10.7	10.9	10.6	12.2	15.8
14	9.0	8.0	12.5	9.9	9.4	12.1	9.9	14.5	11.2	11.8	11.8	11.1	12.7
15	14.4	9.9	13.1	9.4	8.7	9.9	15.2	14.8	10.9	16.9	17.2	12.5	10.2
16	16.7	12.7	12.1	12.4	11.1	12.4	6.6	10.8	11.5	15.2	15.0	9.5	15.8
17	15.4	10.2	11.5	12.2	13.0	11.6	8.7	12.4	12.0	7.5	10.1	9.8	14.8
18	9.7	8.4	8.1	9.9	11.2	12.2	9.2	11.6	7.4	9.7	12.5	12.5	13.8
19	12.0	8.0	11.3	10.2	10.2	13.9	11.7	9.3	10.1	8.9	9.9	7.5	11.7
20	14.9	9.7	12.0	11.7	9.9	12.4	14.0	9.2	14.6	9.3	15.7	9.9	9.2

Appendix 3. Analysis of Variance Tables For CU (%), DU (%) and Water Loss (%)

```
                     Analysis of Variance Procedure
                       Class Level Information

              Class    Levels      Values

              PAT         3      REC SQ TRI


            Number of observations in data set = 78



Dependent Variable: CU
                               Sum of          Mean
Source               DF        Squares         Square         F Value     Pr > F

Model                 2     131.3361000     65.6680500     0.67     0.5156

Error                75    7369.5122962     98.2601639

Corrected Total         77    7500.8483962

              R-Square           C.V.       Root MSE            CU Mean

              0.017509       12.54622       9.912626          79.0088462


Dependent Variable: DU
                              Sum of          Mean
Source               DF        Squares         Square        F Value     Pr > F

Model                 2     158.1951692     79.0975846     0.50     0.6098

Error                75   11914.0782154    158.8543762

Corrected Total         77   12072.2733846
```

```
 R-Square          C.V.      Root MSE           DU Mean

 0.013104       18.39095      12.60374          68.5323077

Dependent Variable: LOSS

                              Sum of          Mean
Source                 DF       Squares        Square   F Value     Pr > F

Model                   2     162.2862769     81.1431385      0.31     0.7317

Error                  75   19402.0282885    258.6937105

Corrected Total         77   19564.3145654

              R-Square          C.V.      Root MSE          LOSS Mean

              0.008295       55.98989      16.08396          28.7265385


             Duncan's Multiple Range Test for variable: CU

        NOTE: This test controls the type I comparisonwise error rate, not
              the experimentwise error rate

                  Alpha= 0.05  df= 75  MSE= 98.26016

                    Number of Means     2         3
                    Critical Range      5.482    5.765

        Means with the same letter are not significantly different.

             Duncan Grouping             Mean      N  PAT

                       A                  80.235     26   TRI

                       A                  79.578     26  SQ
```

```
                     A                       77.213     26  REC


                Duncan's Multiple Range Test for variable: DU

        NOTE: This test controls the type I comparisonwise error rate, not
              the experimentwise error rate

                Alpha= 0.05  df= 75  MSE= 158.8544

                  Number of Means     2          3
                  Critical Range        6.970   7.330

        Means with the same letter are not significantly different.
            Duncan Grouping              Mean      N     PAT
                     A                   69.891     26    TRI

                     A                   69.141     26     SQ

                     A                   66.565     26  REC

  Duncan's Multiple Range Test for variable: LOSS

        NOTE: This test controls the type I comparisonwise error rate, not
              the experimentwise error rate
                Alpha= 0.05  df= 75  MSE= 258.6937
                  Number of Means     2     3
                  Critical Range  8.895 9.354

        Means with the same letter are not significantly different.

            Duncan Grouping              Mean      N  PAT

                     A                   30.050     26  SQ

                     A                   29.410     26  RC

                     A                    26.720     26  TR
```