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The Development of A mathematical Model to Predict Runoff From A micro-catchment under High Water Application Rates

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ABSTRACT

Current trends in sprinkler irrigation to improve application uniformity and reduce energy requirements have led to problems of water application and potential surface runoff, which in turn have highlighted the importance of the soil and cultivation practice in making best use of irrigation water.

The objective of this study was to begin the development of a mathematical model, which will simulate the operation of current sprinkler-soil-crop system, in order to provide a means of predicting surface runoff and so provide a more effective approach to system design.

A model has now been developed which will predict runoff from a small simple agricultural catchment in the form of a ridge and furrow cultivation system. The model is based on the kinematic wave theory involving the continuity equation and the simplified momentum equation. A four-point implicit finite difference scheme is used to solve numerically the kinematic wave equations. The model (SROFF) may be used to predict the runoff at various times from a simple catchment with different slopes, water application rates and soil infiltration rate. A further development of the model was made by the introduction of the interception loss model (INCEPT) to predict the amount of water intercepted by the crop canopy during irrigation.

The validity of the model was tested and supported by the results of laboratory experiments conducted on two soil samples

with different infiltration rates, using three different application rates. The performance of the model was also evaluated by statistical test. There was good agreement between experiment and model results.

The results indicated that this model can provide valuable information for the effective design of sprinkler systems, particularly where runoff may be a potential problem. This is particularly the case with current low pressure irrigation systems but equally the problem is common with high pressure systems when applied to soils with low infiltration rates.

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List of symbols

Symbol	Description	Dimension
A	Irrigated area	m2
AR(t)	Application rate at a particular point	mm/hr
b	Constant depends on nozzle type	
Bl	Drainage parameters	
C	Infiltration constant	mm/hr
cl	Constant depends on nozzle type	
cf	Conversion factor	
Cs	water stored on the canopy during irrigation	mm
Cu	Christiansen's uniformity coefficient	
D	Exponent for overland flow that is related to flow regime	
d	Nozzle diameter	mm
Da	Actual cumulative depth of infiltration	mm
Dn	Net depth of water applied	mm
Dp	Potential cumulative depth of infiltration	mm
Dr	water drained fron the canopy	mm/hr
E	Evaporation rate	mm/hr
Ei	Irrigation efficiency	(%)
Fo	Froude number	
g	Acceleration due to gravity	m/sec2
h	Depth of flow	mm
ho	Initial depth	mm
Hp	Peak application rate	mm/hr
Ht	Total dynamic head	m
Hn	Normal depth at the down stream end	mm

List of symbols (continued)

Symbol	Description	Dimension
Hz	Nozzle height	m
I	Infiltration rate	mm/hr
Im	Potential infiltration rate	mm/hr
Ip	Infiltration after ponding	mm/hr
Is	Interception loss	mm
k	Infiltration constant	
K	Kinematic wave number	
k1	Drainage parameters	
L	Length of plane	m
M	Mean value of observations	
N	number of observations	
n	Manning's roughness	
n1	Infiltration constant	
O	Constant depends on the tree species	
P	Operating pressure at the nozzle	kpa
PE	Pumping energy required	megajoules
Pes	Energy saving	(%)
Pt	free throughfall	(%)
Q	Net input of water to the canopy storage	mm/hr
q	Discharge per unit width	m2/sec
Qm	Measured runoff at a given time	mm/hr
Qp	Predicted runoff at a given time	mm/hr
Q	Mean measured runoff rate	mm/hr
R	Application rate	mm/hr
r	Radius of throw	m
Rf	Neutron probe reading	
RG	Gross rainfall rate	mm/hr

List of symbols (continued)

Symbol	Description	Dimension
Rw	Neutron probe standard water reading	
Rx	Rainfall/irrigation excess	mm/hr
Sf	Friction slope	
S	Plane slope	
s	Standard deviation	
Sc	Water stored on the canopy after irrigation and leaf drip ceased	mm
t	time	hr
to	Initial time	hr
Tp	Time to the peak rate	hr
Tpo	Time of ponding	hr
V	flow velocity	m/sec
Vo	Normal velocity at the down stream end	m/sec
W	Plane width	m
X	Distance	m
x	Absolute deviation from the mean of individual observations	
Zf	Falling distance	m
t	Time increment	sec
ΔT	Time difference between the cylinder infiltration curve and the intersection of the modified curve with application rate	hr
Δx	Distance increment	m

List of symbols (continued)

Symbol	Description	Dimension
α	Coefficient for overland flow that is related to surface roughness and geometry	
θ	Angle between the axis of the nozzle and the horizontal plane	degree
θv	Volumetric water content	cm3/cm3

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

An expansion of irrigated land and rehabilitation of existing irrigation systems is seen by many people as a prerequisite for increased agricultural production to feed the growing population of the world. In some countries the basic resources of agricultural production, land, water, energy, and labour are becoming scarce, or expensive to exploit and so can limit the desired expansion of area under irrigation. Hence, judicious use of these resources is most important in the future.

Several irrigation methods are used and sprinkler irrigation is one of them. Sprinkler irrigation has a distinct advantage over more traditional surface irrigation methods because it can cope easily with uneven topography, sandy soils, or variable water infiltration rates. The area under sprinkler irrigation has steadily increased in recent years and now represents about 5% in area terms of world irrigation (approximately 10 million hectares). Although sprinkler irrigation is unlikely to replace surface irrigation as the most important irrigation method in the foreseeable future, its use in areas where more control over irrigation efficiency is required will undoubtedly increase. Sprinkler irrigation is also likely to develop from the use of the more labour intensive handmove systems to moving sprinkler systems such as rainguns, lateral move, and center-pivot systems.

One major problem with this however is the increase in energy required to operate sprinkler systems. This has led to more interest in irrigation scheduling, improving pumping plant and irrigation application efficiency and modifying systems to reduce pressure and water losses. Pressure reduction can have a significant effect on energy use and hence costs of operation particularly when large quantities of irrigation water are required in the arid regions. Many machines have now been modified to suit lower pressure operation by changing sprinklers and the use of fixed spray nozzles.

1.2 APPROACH TO DESIGN

Sprinkler irrigation design is generally regarded as a hydraulic problem. For conventional stationary sprinkler systems an average application rate of water is selected which is less than the basic infiltration rate of the soil, and the sprinklers are arranged so as to apply a uniform pattern of water to the crop. Typical average application rates range from 5 to 25 mm/hr. A hydraulic system involving pumps, pipelines, and spray nozzles is then designed to meet these basic criteria.

Setting the average application rate less than the basic infiltration rate of the soil is an attempt to ensure that all water applied is absorbed by the soil in order to prevent surface runoff. However, in practice this does not always occur. Instantaneous application rates can be much higher than the basic infiltration rate and runoff can occur. This is particularly true under mobile sprinkler irrigation systems. The introduction of low pressure irrigation system tends to increase the problem of runoff. As the water pressure is lowered the spread of water distribution from individual sprinklers is less, thereby decreasing the area over which the water is applied. This increases the water application rate (often in excess of 100 mm/hr) which may then exceed the soil infiltration rate, thus producing runoff. This effectively reduces the irrigation application efficiency which can mitigate the effect of the energy savings gained through pressure reduction. Such conditions may restrict the use of low pressure system and other moving sprinkler irrigation systems which have high application rates to certain ranges of topography, soil types or tillage and crop management systems.

Much attention is also given to achieving a uniform application of water. The concern of the designer is mostly associated with achieving uniformity of the spray in the air above the crop canopy rather than obtaining a uniform wetting of the root zone or uniformity of water uptake by a crop. Both the interception of water by the crop canopy during irrigation and cultivation practices (e.g. ridge and furrow) can significantly modify the distribution of water and influence the effectiveness of water uptake by the crop and underlines the needs for a more realistic approach to this aspect of design.

It is clear that the current approach to sprinkler design has limitations. There is a need to establish a more appropriate design method which takes account of the crop, soil, and the cultivation practices as well as the spray equipment with the objective of placing water for effective use by the crop, and reducing or eliminating surface runoff. This is particularly so in terms of trends towards low pressure systems.

1.3 OBJECTIVES OF THE STUDY

The objective of this study is to begin the development of a design procedure in the form of a mathematical model which will simulate the operation of a sprinkler-soil-crop system as a more effective aid to design. Figure (1.1) shows a schematic representation of an approach to sprinkler system design. By accurate mathematical simulation of each component, it is planned to simulate water applications by a sprinkler system, its distribution in the soil and uptake by plants. By defining an appropriate objective function it should be then possible to determine the most appropriate water application method in relation to the crop, soil type and cultivation practice.

Since the development of a complete design tool such as that shown in figure 1.1 would take considerable time, this study is limited to a detailed examination of a significant component of the model that of runoff under bare soil and crop cover (figure 1.2) conditions. This is particularly important for low pressure irrigation systems. Although a general model is intended, particular emphasis is given to ridge and furrow cultivations as a common cultivation practice used for growing valuable irrigated crops with sprinkler systems and one which may often exacerbate the runoff problem. It is anticipated that the final model will be of value to irrigation system designers, and to farmers. The following summarizes the objectives of this study :

1- To develop a mathematical model to predict surface runoff from bare soil under sprinkler irrigation systems and in particular low pressure systems with high application rates.

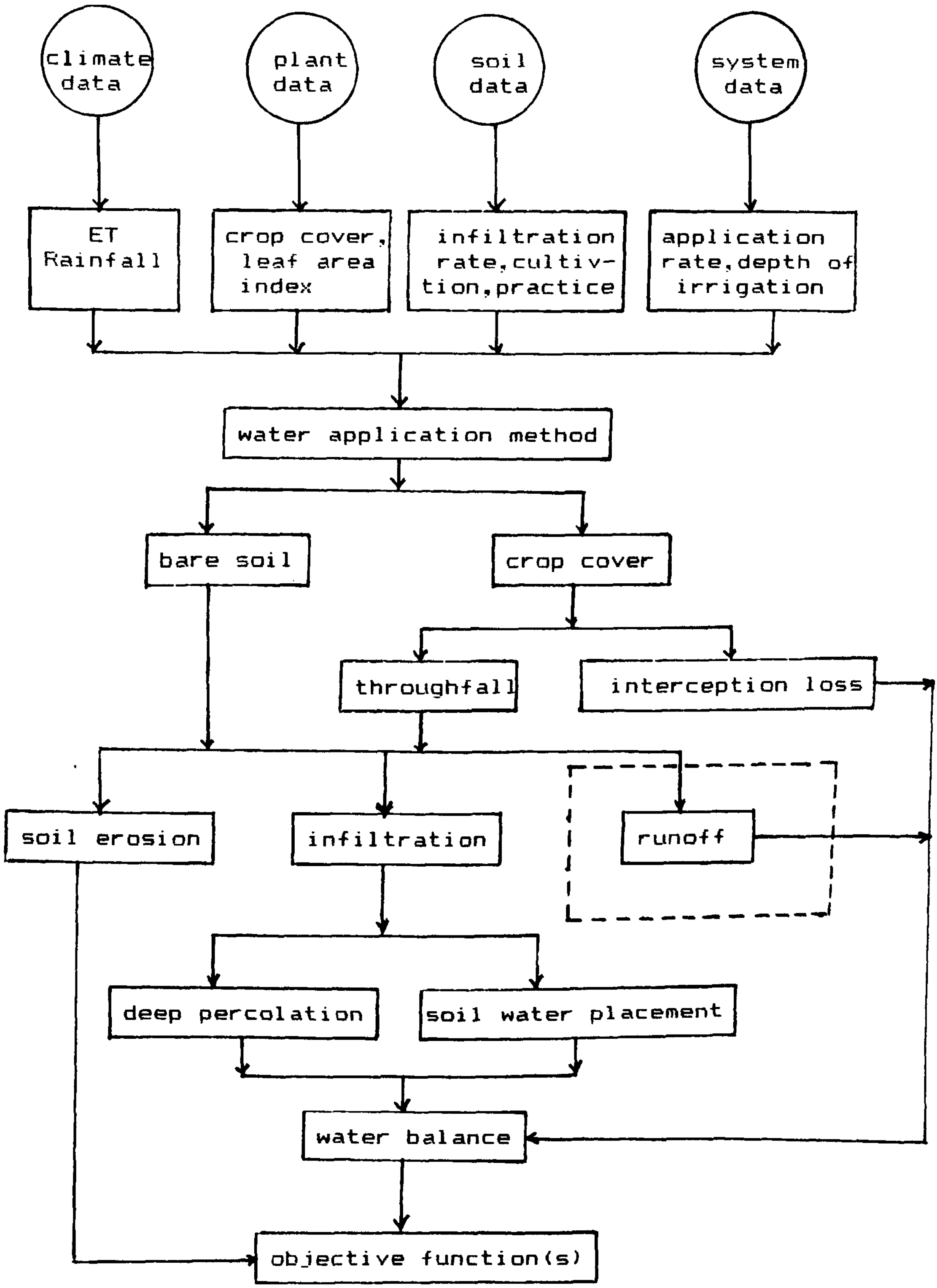


Figure 1.1 Components of sprinkler irrigation system design model.

2- To further develop the model to examine the effects of a growing crop on runoff.

3- To study the influence of cultivation practices on soil water availability to the crop and surface runoff (figure 1.2).

A review is first made of the development of moving sprinkler systems and in particular low pressure developments, and the problems associated with them (chapter 2). This is followed by a review of the development of surface runoff and crop interception models together with various modelling techniques. This leads to the selection of an appropriate surface runoff model and crop interception model suited to the needs of sprinkler systems (chapters 3 and 6).

The construction of the two models is then described in detail including the principles involved and techniques used to provide the required solution. Also the operation of the model is explained including the input required, the output obtained, and the interaction between the two. The relative influence of changes in input and output data and parameters are also tested through sensitivity and statistical analysis (chapter 5).

A series of laboratory experiments are then described which were undertaken to validate the model (chapter 5,7).

A limited field experiment was also carried out to compare different cultivation practices under different application rates to examine their effects on water distribution in the soil root zone, surface runoff (chapter 8).

The conclusions of the study and suggestions for further study are in chapter 9.

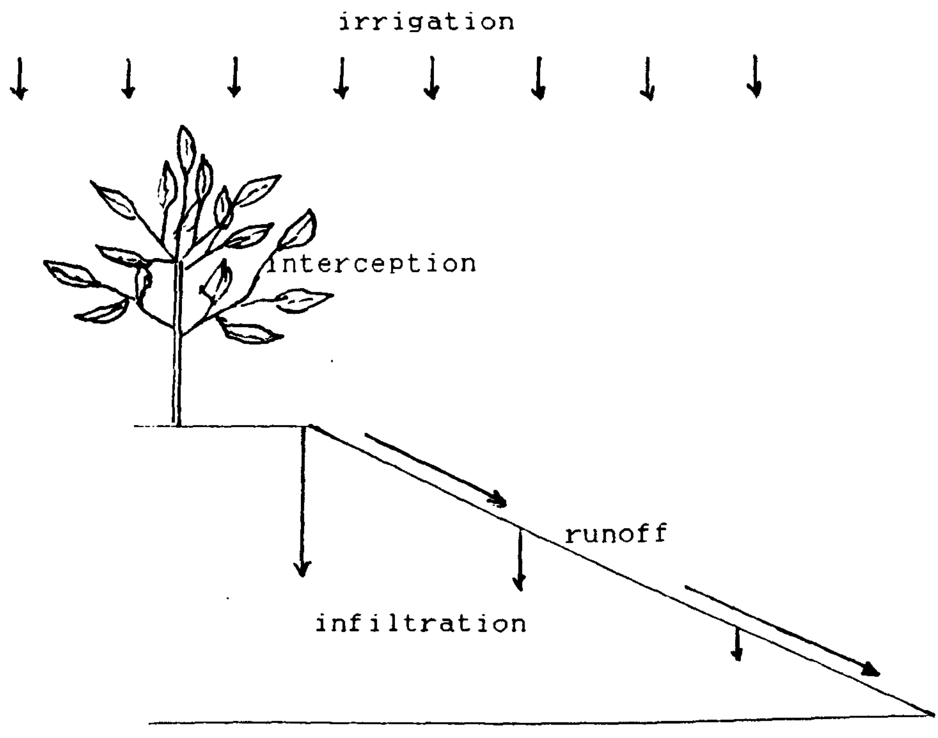


Figure 1.2 Schematic representation of sprinkler irrigation of a row crop grown on ridges.

CHAPTER 2

A REVIEW OF LOW PRESSURE SPRINKLER SYSTEM

2.1 INTRODUCTION

The purpose of this chapter is to review available literature on the development of low pressure irrigation systems and to judge the effects of using such system on water application rate, application uniformity, surface runoff, infiltration, soil erosion, and energy saving.

A definition of what is meant by low pressure can vary a great deal, with such a wide range of operating pressures in use. Sprinkler irrigation systems are often classified according to the nozzle operating pressure. To some, low pressure means 240 TO 275 kpa (35 to 40 ib/in2) or less, whilst others would define it as 40 KPA (6 ib/in2) or less. The classification used for revolving head sprinklers used by the irrigation association in the U.S.A. (Pair et al 1975) is from 34 to 203 kpa (5 to 29 ib/in2), intermediate pressure from 203 to 405 kpa (29 to 59 ib/in2), and high pressure above 405 kpa (59 ib/in2). Withers and Vipond (1980) divided the operating pressure into three categories; high pressure from 483 to 966 kpa (70 to 140 ib/in2), medium pressure from 207 to 483 kpa (30 to 70 ib/in2), and low pressure from less than 207 kpa (30 ib/in2). In this study a system is classified as low if the nozzle operating pressure is less than 100 kpa (15 ib/in2).

Although sprinkler irrigation is a well established method of applying water to crops, in recent years there has been much emphasis on reducing energy costs of systems and more efficient use of water as a limited resource. Coping with increased costs of energy has created more interest in irrigation scheduling, improving pumping plant and irrigation application efficiency and by modifying systems. One such modification is to decrease sprinkler operating pressure by changing from high pressure rotary impact sprinklers to low pressure rotary impact sprinklers and fixed spray nozzles which are designed to operate at low pressure.

Center pivot irrigation systems are designed to apply controlled amounts of water within relatively short time periods, enabling operators to better use available irrigation scheduling procedures which save both water and energy. Unfortunately, two primary limitations of center pivot systems are (1) the high energy requirement for pressurization, and (2) the significant amount of unirrigated land (10-20%) in the corners (Howell and Phene 1983). These limitations can be minimized by using low pressure spray application systems (Gilley and Mielke 1979) and either end-gun sprinklers or cornering-pivot systems. Low pressure spray systems usually have higher application rates than high pressure impact sprinkler systems. The higher application rates can result in increased surface runoff. The runoff can be controlled or minimized by lowering the system capacity, adjusting the application rate pattern, or by various cultural practices (Gilley and Mielke 1979). In areas where good agricultural land is expensive or limited in quantity, lateral-move systems (square or rectangular) have been used as an alternative sincethe late 1970s.

Current farming trends indicate the desirability of developing and improving low pressure irrigation systems. Numerous research studies and development projects have been initiated or discussed to meet these needs. Rawlins et al (1974) used a small plot model involving a travelling trickle irrigation system. Wilke (1976) designed a tractor mounted frame which was capable of moving a single drip lateral over one or either two rows of cotton. Burt and Keller (1976) tested different sprinklers operating at pressure less than 135 kpa, and they suggested that low pressure devices could be use in the future, because they save energy and water. Lyle and Bordovsky (1979) designed a new concept in irrigation sprinkler systems as shown in figure 2.1. They suggested that this system has the potential of saving energy and water. The system called "a low energy precision application "(LEPA) system and they described their systems as a continuous moving rectangular systems. A laser-aligned travelling trickling irrigation systems (TTIS) (Howell and Phene 1983) has also been developed and tested with different applicator irrigation devices. These two mechanically moving irrigation systems extend the trickle irrigation concept to large-scale row crops. These systems utilize a lateral-move sprinkler system mainframe converted to low pressure (30-150 kpa) drop tube structures to apply the water to each row (Phene et al 1985). They offer many of the advantages of trickle irrigation for row crops while reducing some problems such as clogging and extensive pipe networks.

Many irrigation manufacturers now offer low pressure conversion kits for existing high pressure center pivot systems, and lateral move systems. These machines spray the water through

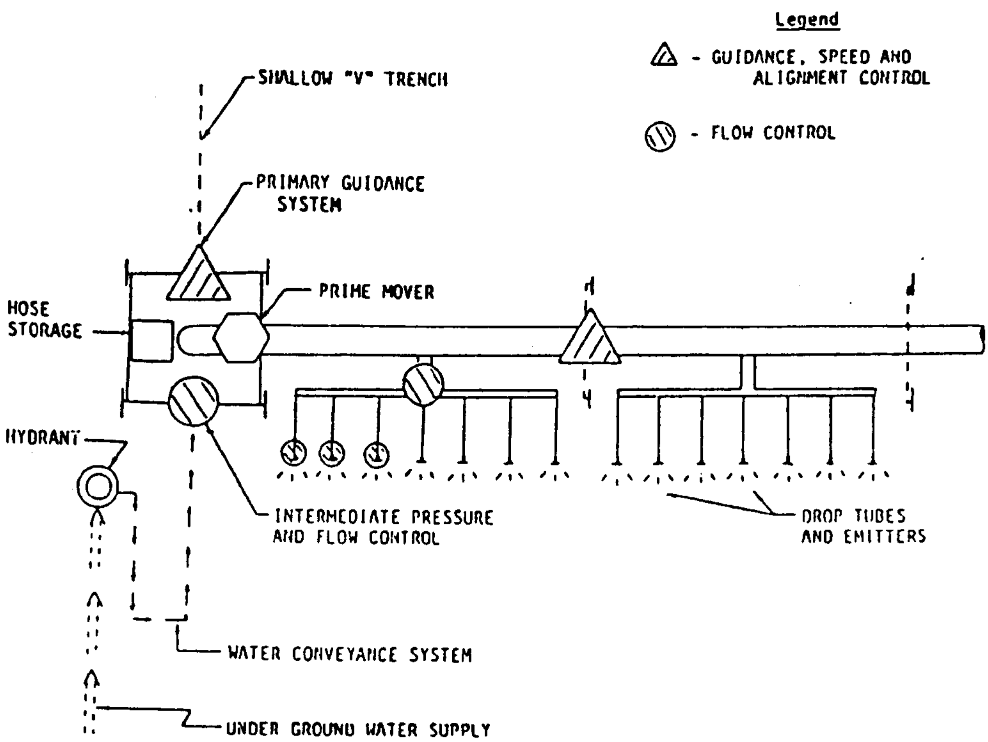


Figure 2.1 Schematic diagram of low energy precision application system (after Lyle 1983).

nozzles towards the soil from a position above the crop canopy. More recently, however several machines have been built with nozzles mounted below the crop canopy by means of drop tubes or orifice controlled emitters, which distribute the water directly to the furrow at low pressure. This occurs as the system continuously moves through the field. Many low pressure irrigation devices have been developed for spraying or releasing water above and below the crop canopy at low pressure. The selection of the device to a particular soil is very important.

2.2 LOW PRESSURE DEVICES

There are many devices that operate at low pressure and are primarily used with moving sprinkler irrigation systems. These devices normally wet a smaller area and so have higher average application rates than more conventional systems. These include low pressure rotary impact sprinklers, and fixed spray nozzles.

Low pressure rotary impact sprinklers (figure 2.2) produce smaller droplets at a lower pressure than do traditional impact sprinklers which operate at high pressure. This is accomplished by passing water through one or more noncircular shaped orifices to spread the jet as it leaves the sprinkler. A fan shaped stream (rather than a tight jet) of water results as shown in figure 2.3. The trajectory out of sprinkler ranges any where from 5 to 25 degrees from the horizontal. This varies the time involved from the water leaving the sprinkler until it hits the soil surface.

Fixed spray nozzles consist of an orifice and a deflector plate, which spreads water to form a part or full circle spray. The deflector plate may be smoothed or grooved, concave, convex

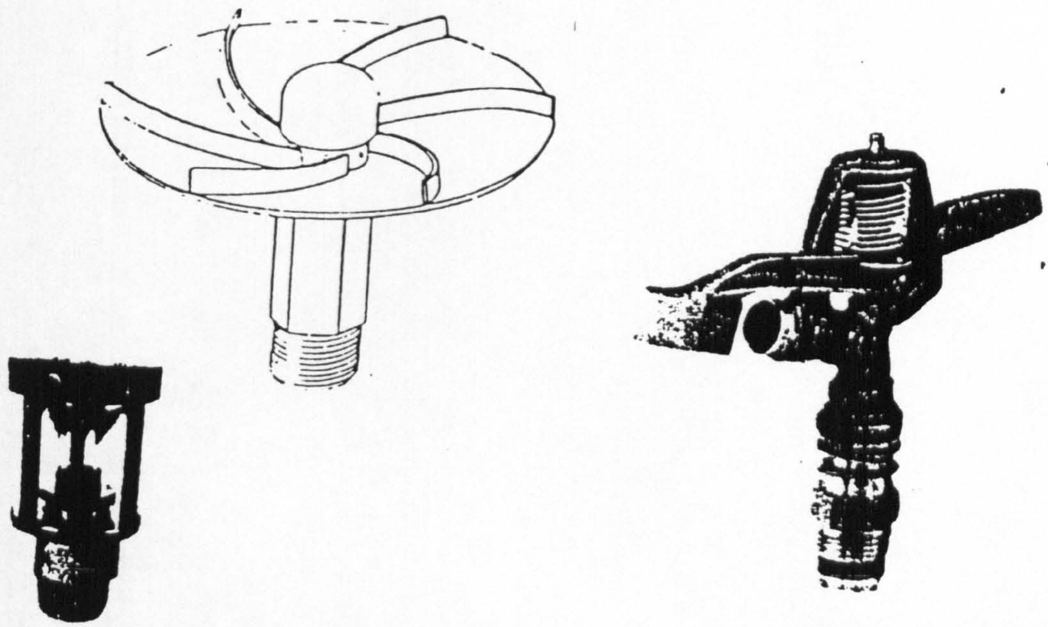


Figure 2.2 Low pressure rotary impact devices (after Young 1981).

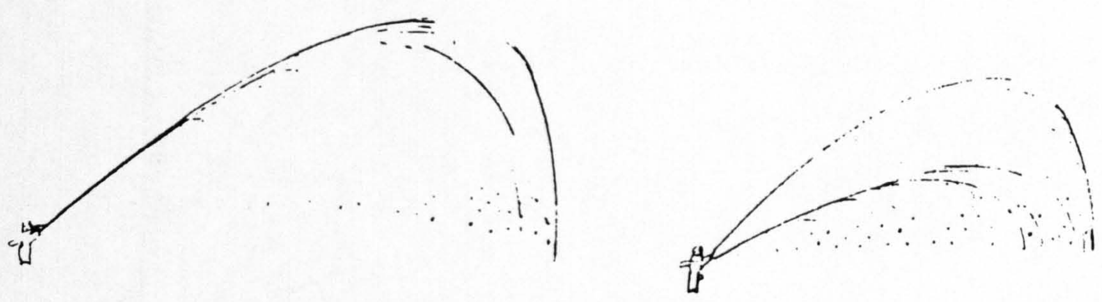


Figure 2.3 Comparison between a concentrated stream and a diffused stream (after Young 1981).

or flat. Water leaves the smooth plate as a mist-like spray and grooved plates as tiny streamlets. In the upright position nozzles with convex plates normally wet the largest area and concave plates the smallest, while the wetted area of flat plates is usually in between. Two such spray nozzles are shown in figure 2.4. The type F nozzle is commonly referred to as a flooding nozzle. After leaving an orifice water impacts on a deflector surface which changes the direction of the water flow and spreads the water. The type R nozzle is called a drift reduction nozzle. This one incorporates a vortex chamber, to produce fewer fine drops than type F nozzles (Solomon et al 1985) for some operating conditions. Another style of irrigation spray nozzle is shown in figure 2.5. The full circle spray is used to spread water over a greater area and thus reduce the average application rate.

The use of low pressure impact sprinklers and fixed head spray nozzles has resulted in several modifications to center-pivot and lateral move irrigation systems. The smaller wetted area of these devices requires closer device spacings. The fixed spray nozzles are placed either on the top, side or underneath the main supply line. The main advantages not only include the reduction of pressure requirement but also possible reduction in evaporation and wind drift because the water can be placed close to the crop canopy.

To further reduce evaporation and wind drift fixed head spray nozzles have been brought closer to the crop and even below the canopy by using drop tubes. Another advantage of the drop tubes or pipes claimed by the manufacturers is that the water is placed below the pipe and below the truss rods; therefore,

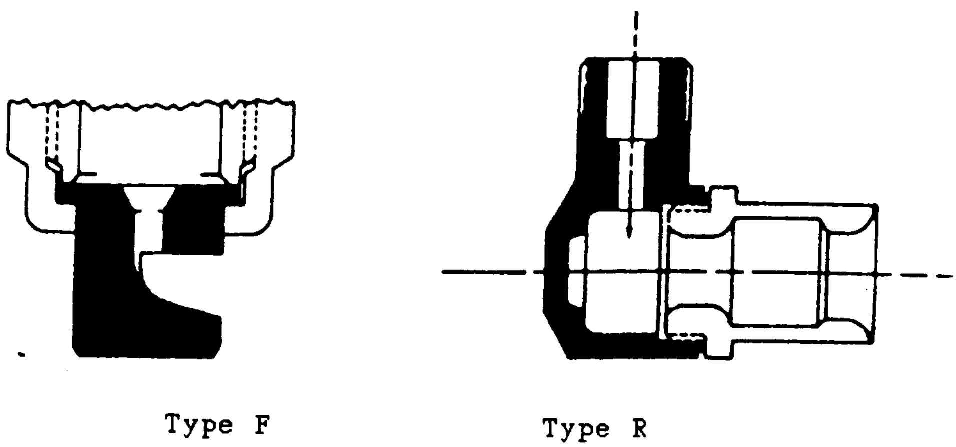


Figure 2.4 Flooding (type F) and drift reduction (type R) style irrigation fixed spray nozzles (after Tate 1977).

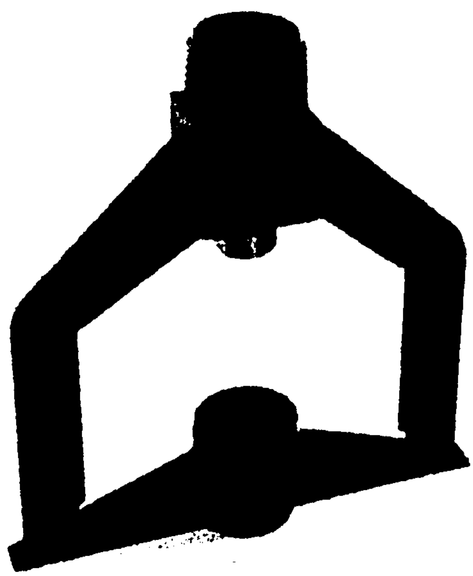


Figure 2.5 Full circle spray nozzle (after Solomon et al 1985).

irrigation can continue during low temperature periods without icing up and collapsing of the system. However, since the spray nozzles are closer to the crop and to the soil surface, the application rate is increased and the potential for runoff and soil erosion increases.

Many manufacturers now make fixed spray nozzles for lateral-move and center-pivot systems. One spray nozzle combines air with the water droplets which the manufacturer claims reduces soil compaction, wind drift, and evaporation.

Another low pressure method of applying water involves dragging polyethylene tubes and applying water as in trickle or drip irrigation. The development of low pressure sprinkler irrigation devices will continue,and the popularity of the system is increasing because of its advantages over conventional systems, especially in areas where there are shortages of water and energy.

The performance of any type of device can be evaluated on the the following points.

Radius of coverage

The radius of throw in turn influences the spacing of laterals, and the sprinkler water application rate. The radius of coverage from a spray nozzle is directly proportional to the operating pressure at the nozzle. Thus a reduction in pressure will directly reduce the throw of the nozzle. Thooyamani et al (1984) conducted an experiment on four types of low pressure spray nozzles, at different heights and pressures. They found a relationship as follows:

$$r = c1 \, [\, d^{1.5} \; Hz^{0.5} \; P^{b} \,] \quad . \quad . \quad . \quad . \quad . \quad (2.1)$$

where:

r = radius of throw (m)
d = the nozzle diameter (mm)
Hz = height of nozzle (m)
P = operating pressure (kpa)

b, cl are constants depend on the nozzle type. For example, for nelson nozzle with flat deflecter plate, b = 0.33, and cl = 0.696. Another relationship was reported by Reddy (1984) between the radius of coverage (r), and operating pressure head at the nozzle (p), by knowing the angle between the axis of the nozzle and the horizontal plane (θ) this relationship is :

$$r = 2 \; P \; SIN \; 2 \; \theta \quad . \quad . \quad . \quad . \quad . \quad (2.2)$$

Drop size distribution

The drop size distribution of sprinkler spray is of practical importance for two reasons (Heerman et al 1980). First, the small droplets are subject to wind drift, distorting the application pattern. Second, large droplets possess greater kinetic energy which transfers to the soil surface, causing particle dislodgement and puddling that may result in surface crusting and runoff. Droplet size is influenced by nozzle characteristics and pressure. Volume weighted mean diameter is proportional to nozzle diameter, and is inversely proportional to pressure with pressure having greater influence for circular nozzles (Kohl 1974). Kohl and DeBoer (1984) tested a 360 degree spray nozzle, with four sizes ranging from 4.8 to 9.5 mm and pressure ranging from 50 to 200 kpa. Smooth and serrated spray plates were used. They reported on drop size distributions for nine different nozzle size, spray plate and pressure combinations that the geometry of the spray plate was shown to influence drop size distribution more than either nozzle size or water pressure, the smooth plate produced the smallest droplets and coarse grooved plate the largest. James and Blair (1984) found that low pressure impact sprinklers produce a smaller droplets at lower pressure than do high pressure impact sprinklers. This was accomplished by passing water through one or more non-circular shaped nozzles to spread (diffuse) the jet as it leaves the sprinkler. Dadiao and Wallender (1985) found that the circular nozzles produced larger droplet sizes than the non-circular nozzles. Also, they found the volume weighted mean droplet diameter was greater for noncircular nozzles at a given distance from the sprinkler, but the maximum droplet diameter was greater for the circular nozzles near the perimeter of the wetted pattern.

Larger droplets are less subject to evaporation and wind drift than are smaller droplets. Sprinkler irrigation evaporation losses have been the subject of numerous field, laboratory, and analytical studies (Frost and Schwalen 1955; Kraus 1966; Stenberg 1967, and Yazar 1984). Loss values obtained from these studies 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 the 10 to 20% range, while the laboratory and analytical values were in the 1 to 2% range. Ali and Barefoot (1978) measured the evaporation loss from a single stationary sprinkler head. They found that for pressure between 134 kpa and 278 kpa evaporation loss remained the same, but at pressure above 278 kpa evaporation loss increased slowly. Edling (1985) developed a model to estimate evaporation and wind drift of droplets from low pressure irrigation devices. He found that evaporation decreases rapidly when droplet diameter is increased from 0.3 mm to 1 mm.

2.3 WATER APPLICATION RATE

A common analytic focus in the literature on low pressure sprinkler irrigation system is the question of whether water is applied uniformly under low pressure. The problem arises because the water application rate at low pressure is usually greater than with conventional high pressure systems. If the average application rate exceeds the soil water infiltration rate then surface runoff can take place (Kincaid et al 1969), resulting in nonuniform water application (Taylor 1986).

The effect of reducing the operating pressure extends beyond pumping costs. There are several different types of sprinkler or spray nozzle application packages from which to choose, but every choice has some disadvantage relative to infiltration of the applied irrigation water. Bernuth and Gilley (1983) state that Low pressure application packages can lead to one or more of the disadvantages listed below:

1- Decreased wetted area leading to reduced application time and increased application rate.

2- Increased droplet size. The increased in droplet size occurs as a results of two factors: a) droplet sizes increase with a decrease in pressure, and b) droplet sizes increase with an increase in nozzle size. Nozzle sizes must be increased to meet flow requirements when operating pressure is reduced.

3- Decreased uniformity of application due to reduced wetted area and terrain induced pressure changes.

Low pressure irrigation systems wet a smaller area than conventional high pressure sprinklers, and thus have higher average application rates (average application rate = sprinkler discharge / wetted area). Most high pressure sprinklers apply water as concentrated streams that wet a point on the soil surface once or twice each rotation of the sprinkler head. Low pressure rotary impact sprinklers or fixed spray nozzles usually either apply water as a spray that cover the entire wetted area continuously or as diffuse (rather than concentrated) streams that wet a point on the soil surface once or twice each sprinkler head rotation. Thus the rate at which water is applied to a given point on the soil surface during an instant of time (i.e. the instantaneous application rate) is usually less for lower pressure sprinklers than for high pressure sprinklers. The average application rates for three different applicator systems of high rotary impact pressure sprinkler, low pressure rotary impact sprinkler, and fixed spray nozzle are compared in figure 2.6. Each is applying the same amount of water, but the application rates distributions are vastly different both in magnitude and time. The smallest wetted area was with the fixed spray nozzle, but produced the highest amount of potential runoff. The higher application rate of low pressure systems will cause more potential runoff on soil with lower infiltration rates.

The rate of water application beneath a center-pivot irrigation system varies continuously with time during the irrigation event. Mathematical expressions for describing the application rate from overlapped individual sprinklers on the

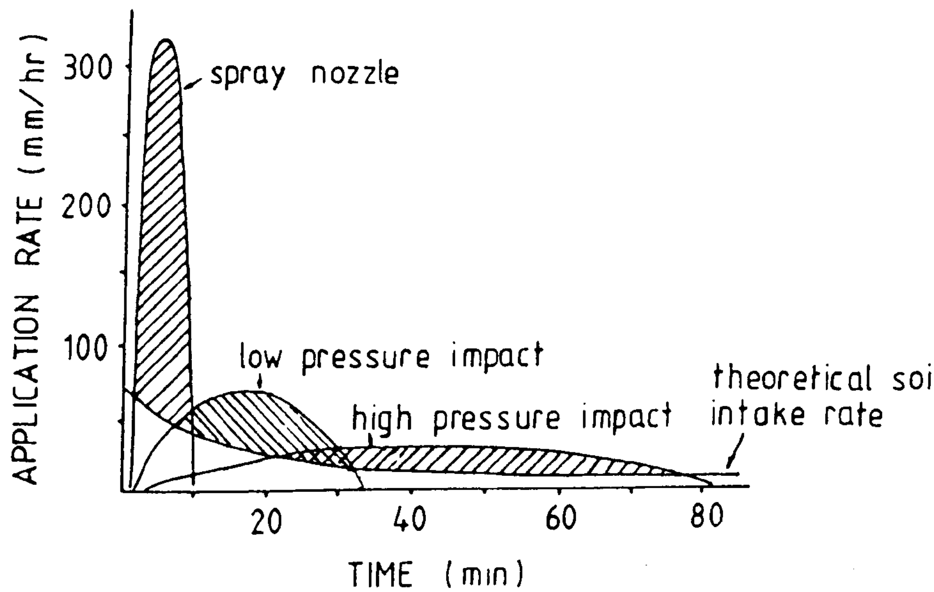


Figure 2.6 Application rate characteristics for three types of sprinkler irrigation systems (after Gilley and Mielke 1980).

center-pivot system have been developed. Heermann and Hein (1968) presented application rate equations for the center-pivot system assuming both triangular and elliptical distribution patterns. Kincaid et al (1969) conducted field experiments to test the validity of the theoretical application patterns, and concluded that the elliptical pattern was most appropriate. Assuming the water distribution of the sprinklers is elliptical, the application rate ar(t) can be written as :

$$AR(t) = Hp/Tp\ (\ 2\ tTp - t^{2.0}\ )^{0.5} \quad . \quad . \quad . \quad . \quad . \quad (2.3)$$

where:

AR(t) = the application rate at a particular point (mm/hr)
Hp = the peak application rate (mm/hr)
Tp = the time to the peak rate (hr)
t = time, starting when the application rate begins (hr)

The choice of application rate to be used with low pressure systems depends on many factors such as soil type, method of application, and soil topography. Lyle (1977) operated low pressure system with an application rate of 100 mm/hr. He reported that no serious damage to soil ridges or basins occurred, and runoff was contained in the soil basins for over an hour of continual application. Harris (1979) on the other hand, applied 890 mm/hr of application rate. He found that soil damage occurred, and it was suggested that soil dikes and ridges would be quickly destroyed, furthermore runoff was evident the instant that the water was applied. This does suggest, that a range of application rates with which further experimental work may be performed, lies within these application rates. This will help to know as to what happens at application rate between these two, and how that could be compared with results from low application rates in terms of water distribution in the soil root zone, runoff, and soil erosion.

2.4 WATER APPLICATION UNIFORMITY

One of the most important conditions for achieving irrigation efficiency and saving water and energy is certainly the uniformity of application over the irrigated area (Ring and Heerman 1978). Christiansen's coefficient of uniformity is generally used as a basis for describing the uniformity of water distribution in sprinkler (Christiansen 1942). The formula used in calculating the uniformity coefficient is:

$$CU = 100(1 - \Sigma x/MN) \quad . \quad . \quad . \quad . \quad . \quad (2.4)$$

where:

CU = Christiansen's uniformity coefficient
x = is the absolute deviation from the mean of individual observations.
M = is the mean value of observations.
N = is the number of observations.

Heerman and Hein (1968) found CU values for high pressure systems were between 87% and 90%, where as Pair (1975) found CU values were between 70% and 89%. Lower uniformity for high pressure systems were caused by poor design criteria that ranged from lack of filters to prevent nozzle blockage to incorrect sprinkler sizing (Gilley et al 1980).

High pressure systems generally have good application uniformities because of the large overlapping pattern of the individual sprinklers. On low pressure systems, the use of lower pressure devices can affect the uniformity of application. The pattern of water distribution within the wetted area of some low pressure devices differ from the distribution pattern for conventional high pressure sprinklers. Instead of having triangular or elliptical shaped distribution patterns (figure 2.7) (i.e. the depth of application rate increasing linearly from the outer edge of the pattern toward the sprinkler) many low pressure fixed spray nozzles have dough-nut shaped patterns (i.e. most water is deposited in a ring near the outer edge of the pattern (James et al 1982; Thooyamani et al 1984). This can adversely affect the uniformity of application for low pressure irrigation systems. Other possible uniformity of application problems associated with low pressure devices include increased wind distortion of application patterns and the interference of distribution patterns of adjacent lower pressure applicator systems on center-pivot laterals (James et al 1982). Because droplets from some lower pressure devices are much smaller than from high pressure sprinklers (Stillmunks and James 1982), distribution patterns from these devices are more subject to wind distortion. Spray from adjacent fixed plate lower pressure devices that wet their entire wetted area continuously can collide resulting in region of intense application and lower system uniformity (James et al 1982).

Several investigators have evaluated the water application uniformity of low pressure irrigation systems. Lyle and Bordovsky (1979) with their LEPA system found that a higher application uniformity with the LEPA system operating at low pressure, compared to conventional sprinklers. The low pressure sprinkler system was tested at different field conditions to determine the water application uniformity. James and Stillmunks (1980) measured the application rates of four different low pressure devices on center pivots under field conditions and found that no difference between the average application rates of

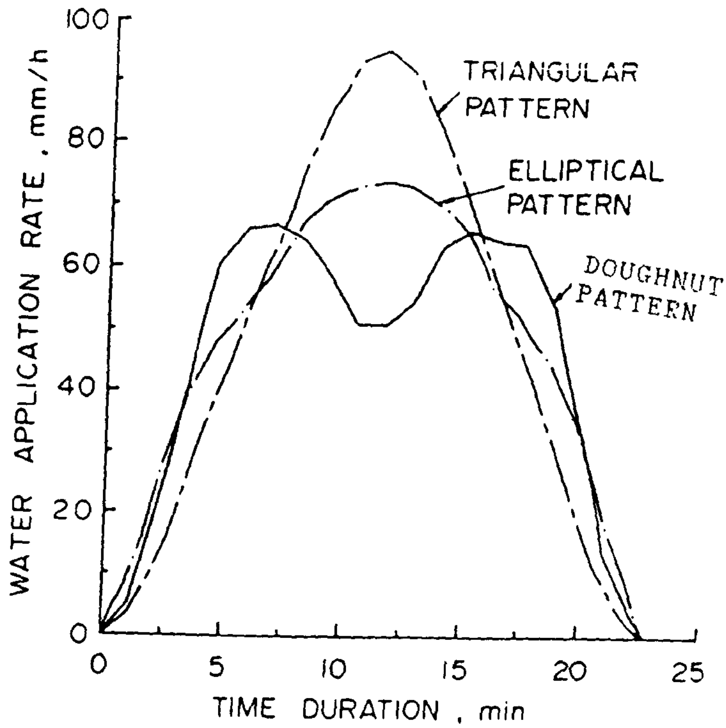


Figure 2.7 Different application rate spray patterns (after Thooyamani et al 1987).

15 and 6 degrees rotary impact sprinklers. They also reported that rotary impact sprinklers produce greater instantaneous application rates than the fixed spray nozzles, and that wind may decrease the application rates.

Nir et al (1980) reported that the values of uniformity coefficient range from 84% to 94% for a self propelled irrigation systems at very low pressure for furrow drop-tubes, and from 71% to 94% for the spray nozzles. The operating pressure used was 47 to 100 kpa. Ali and Borefoot (1978) used the results of a single rotary impact sprinkler or fixed spray nozzle tests to evaluate the application uniformities for a semi-circle spray nozzle, a 6 degree impact sprinkler and 26° impact sprinkler. They found that the application uniformities for the 6 and 26 degrees rotary impact sprinklers were estimated to be comparable for center pivot use. However, the 6 degree impact sprinkler had a 7% smaller wetted diameter which would increase the average application rate and decrease the wetted area. They also observed less pattern distortion from the wind as application rates increased.

Lyle and Bordovsky (1982,1983) compared the field performance of their LEPA irrigation system which distributes water directly to the furrow at very low pressure through drop tubes and emitters which are located at height of 50 to 100 mm above the furrow with high pressure rotary impact sprinklers. They found that wind affected the water distribution from the impact sprinklers, but had little effect on the LEPA system, and the average water distribution uniformities were 90% and 96% for the impact sprinklers and lepa systems, respectively. They also found no difference in water distribution uniformity between 20 degree rotary impact sprinkler operating at 379 kpa and an 80 degree rotary impact sprinkler with a diffuser nozzle operating at 138 kpa.

Gilley et al (1983) evaluated a center pivot irrigation system fitted with high pressure rotary impact sprinklers, low pressure rotary impact sprinklers, and low pressure fixed spray nozzles. The operating pressures ranged from 145 to 427 kpa. They found that the radial and rotational uniformities of water application associated with high and low pressure sprinkler impact systems were compared approximately the same, and somewhat greater than those for the low pressure spray nozzles. Howell and Phene (1983) used a low pressure move lateral system. They tested six different water applicator systems, and distributing the water above and below the crop canopy. The operating pressure ranged from 84 to 167 kpa. They found that the static coefficient uniformity of the system may exceed 96% and dynamic coefficient uniformity was 90%. They stressed that the travel velocity played an important factor in achieving a uniform application with low pressure systems. James and Blair (1984) used a computer simulation model to compare the effect of sprinkler spacing and terrain on theoretical performance of a conventional center pivot and five different low pressure center pivot applicator systems. Operating pressure ranged from 140 to 200 kpa. They found that systems with conventional high pressure sprinklers and low pressure fixed head spray nozzles had the highest uniformities for constant spacing of 12 m and 1.5 m, respectively.

Nimah et al (1985) evaluated low pressure center-pivots in Saudi Arabia under different wind speed and operation pressures.

They found that the maximum distribution uniformity (DU) and the potential application efficiency (PAE) for fixed spray nozzles were 82.5% and 75.5% respectively. They suggested that for a good DU and PAE under high wind conditions the pressure should be increased. Hanson et al (1983) studied low pressure sprinkler system under different wind conditions and operating pressures using 24 different applicator systems. He suggested that for a good water application uniformity under high wind conditions the spacing between the nozzles should be decreased. Thooyamani et al (1987) tested the performance of low pressure center-pivot sprinkler systems, uniformity of application was evaluated under six different applicator systems. They found that the low pressure systems distributed water at or above the generally acceptable level of uniformity (80%) only 37% of the time. It was also found that the six applicator systems distribute water consistently below their design uniformity, this was because a poor design in the system. Thooyamani and Norum (1987) studied the performance of low pressure center-pivot systems. They concluded that the uniformity of application in both circular and radial directions was evaluated under eight different applicator systems, and it was found that all the systems were distributing water above the generally accepted level of uniformity (80%).

Low pressure systems require the sprinkler spacing to be closer and the radius of throw of the individual sprinklers or nozzles will be much less than that for high pressure systems, resulting in less overlap of the application pattern for the individual applicators. This reduced pattern overlap could result in a lower uniformity. Care should be used in selecting sprinkler spacings and nozzle sizes to ensure an acceptable uniformity of pattern for low pressure systems. The topography of the land can affect line pressure causing uneven discharge from sprinklers. However, the effects can be taken into consideration during design and pressure regulators can be used to overcome part or all of the discharge variations.

Management practices such as maintaining nozzle pressure, keeping nozzles free from clogging, etc., help the system to perform according to design. Failure to maintain the system may result in low uniformity of application of water.

The uniformity of application under the low pressure systems may improve considerably if the redistribution of water within the soil profile is taken into consideration. Hart (1972) showed examples of uniformity coefficient of 60% for the water distribution at the ground surface from center pivot system, becoming 76% and 86% after redistribution in the soil for 1 and 2 days, respectively. The effect of redistribution within the soil is of course much dependent upon the spatial distance between above-average and below-average application (Thooyamani and Norum 1987).

2.5 SURFACE RUNOFF

When the water application rate of any irrigation system exceeds the soil infiltration rate, the potential for surface runoff exists. The higher application rate of low pressure systems can thus cause more potential runoff than conventional systems (figure 2.6). Potential runoff is defined as noninfiltrated water in transient state, plus the temporary storage of noninfiltrated water in surface depression (Kelso and Gilley 1983). The amount of actual surface runoff that occurs depends on the extent of surface storage immediately available. Soil crusting can also inhibit soil infiltration and increase surface runoff. The finer the soil texture and the steeper the soil topography the lower the infiltration rate (Gilley et al 1983). Thus fields with finer textured soils and uneven topography are doubly vulnerable to possible greater surface runoff as a result of using low pressure irrigation systems.

The surface runoff hazard is the greatest obstacle for low pressure sprinkler irrigation systems. Surface runoff reflects the interaction among the hydraulic characteristics of the sprinkler, the soil-crop system and the management practices of the irrigators. The impact of management is difficult to consistently reproduce and quantify, however, it is often the most important factor to consider. Several investigators have acknowledged the runoff problem with sprinkler systems. Pair (1968) reported that the maximum application rates under center-pivot machine often exceeds the infiltration capacity of agricultural soils. Kincaid et al (1969) found that runoff values as high as 22% of water applied under high pressure sprinkler systems on a silt loam soil. Addink (1975) found runoff values as high as 65% under a low pressure spray system on a very fine sandy soil in comparison to 22% under a high pressure sprinkler machine. They also reported no runoff problems on a sandy soil with either high pressure sprinklers or spray nozzles. Gilley and Mielke (1980) reported that runoff on corn plots was measured for high pressure rotary impact sprinkler, low pressure rotary impact sprinkler, and fixed spray nozzle systems. They found that runoff was 25%, 9%, and 28% of the amount of water applied for the high pressure impact sprinkler , low pressure sprinkler impact, and low pressure spray nozzle systems, respectively.

Several investigators have acknowledged the runoff problems with moving sprinkler irrigation systems, and they have developed empirical or semi-empirical methods to predict the potential runoff, Kincaid et al (1969), Dillon et al (1972), and Addink (1975). Recently, several authors have used physically based infiltration equations to predict infiltration and potential runoff with variable application rates, Slack (1978), Hachum (1976), Hachum and Alfaro (1976, 1977, 1980). But all these equations have not been used for high pressure sprinkler systems to predict surface runoff nor from the low pressure systems.

The amount of surface runoff will depend upon several factors, such as antecedent soil moisture, depth of water applied, soil type, and tillage practices. To reduce the amount of surface runoff appropriate tillage can be effective in reducing runoff. When the soil surface is rough water applied at a rate greater than the soil infiltration can be stored on the soil surface and the runoff is reduced and may in some case become negligible (Burwell and Larson 1969, Dillon et al 1972). Several researchers have investigated ways of reducing surface runoff. They reported that extensive profile modification such as moldboard plowing (Musick and Dusek 1975; Musick et al 1980) or thorough mixing with a ditching machine (Eck and Taylor 1969) can increase water infiltration under graded furrow irrigation.

Another tillage system is furrow diking (figure 2.8). This is also known as tied-ridging, or row-damming and involves forming small dikes across furrows to prevent runoff. Aarstad and Miller (1973) investigated the effet of small basins between

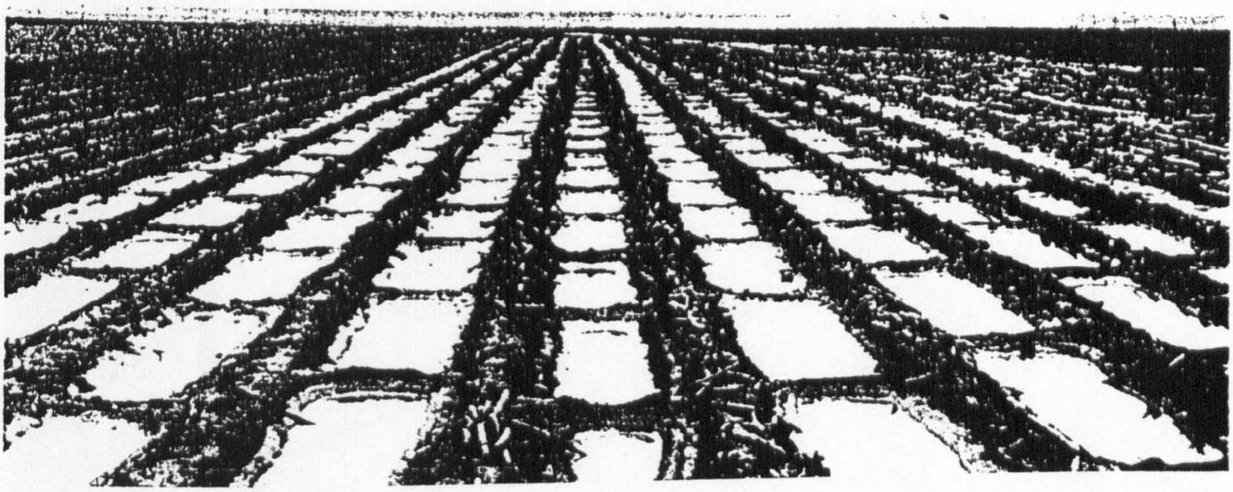


Figure 2.8 Furrow dikes conserving runoff (after Krishma et al 1987).

crop rows. They reported that runoff has been reduced from about 40.0% to 1.0% under center-pivot sprinkler system. Also the furrow diking was suggested by Lyle and Dixon (1977) and Lyle and Bordovsky (1979, 1980) to reduce or eliminate runoff. Jones and Clark (1987) and Gerad et al (1987) reported that the tied-ridge system reduced runoff and increased crop yield.

Gilley and Mielke (1980) concluded that low pressure will save energy, but could create management problems, such as surface runoff, and soil erosion. They suggested that the surface runoff may be reduced by using one or more of the following, reduced system capacity, increased travel velocity, modified application rate pattern, and modified cultural practices.

Lyle and Bordovsky (1982) reported from their experiment, that there was evidence of increased surface runoff with the use of 138 kpa sprinkler when compared with 379 kpa sprinkler. Gilley et al (1983) used a combination of field experiments to determine the impact of low pressure rotary impact sprinklers and spray nozzles on surface runoff, saving energy, and crop production. Different tillage methods were incorporated into the investigations. They concluded that surface runoff occurred only with low pressure spray nozzles, and in introducing the chisel treatment, however reduced the surface runoff. Howell and Phene (1983) used a slot-mulch tillage system and compared with conventional tillage for water infiltration and yield in cotton production. The results of their study showed that cotton yields were not influenced by type of water applicator, but were 25% higher under the slot-mulch tillage system. DeBoer and Beck (1983) carried out three primary tillage and one secondary tillage treatment are incorporated into the experiment. They reported that the surface runoff was increased with low pressure applicator systems, and soil water contents decreased with a decrease in operating pressure, and reduced tillage methods are associated with significant reduction in surface runoff. Wilhelm et al (1984) conducted an experiment to determine the influence of low pressure center-pivot irrigation system in combination with various tillage methods on corn yield. They concluded that tillage methods are needed to increase water infiltration or provide temporary surface storage of water for the successful use of low pressure systems on some soils. Undersander et al (1985) studied the effect of tillage methods on runoff, using different pressure devices. With operating pressure ranging from 172 to 414 kpa. They found that the surface runoff was greater from the low pressure system with fixed spray nozzles than from that of high pressure system with impact sprinklers. Also they found that deep ripping reduced the runoff, while furrow diking completely eliminated it.

Recently an implement with a trade name " Dammer-diker " was developed to reduce runoff problems in areas irrigated with low pressure irrigation systems. It punches large holes in the ground at an adjusted depth after loosening the soil with shanks. Pitting increases soil surface storage and thus opportunity time for infiltration is increased. Pitting also disturbs the soil to a considerable depth when the pits are made by protecting the soil in the pits against droplet impact after ponding, the infiltration capacity is also increased. Oliveira et al (1987) studied the effect of pitting on infiltration and runoff under sprinkler irrigation. They found that runoff decreased with increased area of water storage provided by pits and infiltration increased.

Most previous research on the effect of slope was devoted to studies of soil erosion problems, or the mechanics of runoff flow, and relatively little research has been conducted to evaluate the runoff from irrigation. Nevertheless little is known as to what happens at steep slopes such as that of ridge sideslopes, and how that could be compared with results from less slopes. Therefore, using high application rates and steep slope to predict the amount of runoff are lacking in the literature. Also cultivation can be as important to the efficient use of irrigation water as it can be to other aspects of production by, encouraging rapid infiltration, storing water on the soil surface while it infiltrates or controlling the surface movement of water to some point where it can infiltrate most effectively(Kay 1988).

2.6 INFILTRATION

Soil infiltration rate affects the rate of runoff which is important in the prediction of water loss under irrigation and soil erosion. Infiltration is affected by properties of infiltrating fluid and soil factors which include both soil hydraulic properties, and initial and boundary conditions in the profile. The basic infiltration (intake) rate is a familiar concept in irrigation practice, although it is not well defined. There is no standard or generally accepted methodology for estimating the basic infiltration rate for a given soil. Theoretically the basic infiltration rate should be close to the saturated hydraulic conductivity of the soil.

Water infiltration under a relatively high irrigation intensity and lasting for a relatively long time period can be divided into two major stages: (1)- pre-surface saturation, and (2)- after surface saturation. In the pre-surface saturation stage the infiltration is governed by the rainfall characteristics. Therefore, during this stage the infiltration rate equals the instantaneous rainfall rate. Once surface saturation is reached, a flood type of infiltration takes place after surface saturation time runoff becomes potential, because the infiltration drops below the application rate. Thus infiltration during the second stage or the post surface saturation stage is controlled by the characteristics of the soil profile.

There are two primary types of instrumentation for obtaining point infiltration data : (1) cylinder or flooding infiltrometers, and (2) sprinkling infiltrometers. Many investigators describe the use of flooding infiltrometers in the irrigation and hydrologic contexts, respectively. However, many researchers caution against the use of cylinder infiltrometers for obtaining measurements of infiltration meant to be used in the precipitation or sprinkler contexts. However, Neff (1979) reported that statistical analysis of the results of 50 double-ring infiltration tests and 44 drop-forming infiltrometer tests failed to demonstrate significant difference in the final infiltration rates determined by the two methods. On the other hand, Rubin (1966) mathematically demonstrated that the infiltration curves obtained under flooding conditions in uniform soil were not the same as those obtained under rainfall conditions, the greatest difference being noted in the early stages of post-ponding infiltration. Field tests of sprinkling and flooding infiltrometers also revealed differences in the final rate, Amerman (1983).

It is clear that pre-ponding infiltration equations cannot be physically investigated without a sprinkling applicator. Macropore infiltration work indicates that ponding on interpore areas contributes runoff to the macropores, so a sprinkling applicator is essential for these studies .

2.6.1 Effects Of Application Rate On Infiltration

Surface conditions have a marked effect on the infiltration process. The formation of surface seals or crust on bare soils is an important problem in irrigation. it reduces infiltration and increases surface runoff. Surface seals form under the influence of external factors, such as rain drop impact and mechanical compaction. Mcintyre (1958) found a relationship between soil splash and the formation of surface crust by rain drop impact. He concluded that a decline in soil splash rate is due to crusting or sealing the soil surface. The formation of surface crust was found to be due mainly to washing-in of fine particles and compaction of the immediate surface by rain drop impact. Bouma et al (1971) used the methods of Hillel and Gardner (1969,1971) to measure the unsaturated hydraulic conductivity in the field by infiltration through an artificial crust. K-values were determined from the rate of infiltration into crusted soil columns 300 mm in height that carried out in situ.

Several other investigators, such as Dueley (1958), Mannering and Meyer (1961), and Schmidt et al (1964) refer to the phenomenon of soil surface sealing, and attribute much of the decrease in the infiltration rate to unprotected soils. Edward and Larson (1969) analysed the effect of surface sealing on infiltration. Seals were formed on tilled soil materials by using rainfall simulator and a numerical solution to the Richard equation proposed by Hanks and Bowers (1963) was used to describe the effect of a developing surface seal upon infiltration. They found that predicted two-hour infiltration was reduced by as much as 50% by surface sealing. Schmidt et al (1964) found a very rapid decrease in infiltration during the first 15 minutes of rainfall, followed by a nearly constant infiltration rate after 30 minutes of exposure. Similar results were obtained by Moldenhaur and Long (1964) who implied that a amount of kinetic energy was required as rainfall to affect surface sealing and initiate runoff. Meyer (1958), and Moldenhaur and Kemper (1969) demonstrated the pronounced effect of rainfall energy on the surface layer, and that of the surface layer on infiltration into undisturbed soil profiles. Tripplet et al (1968) showed that a higher rate of infiltration occurs with an increase in the percentage of surface covers. Skaggs et al (1969) found that the infiltration for a bed covered of Zonesville silt loam wa much higher than for cultivated fallow plots under similar conditions. Infiltration for cultivated plots was in turn much higher than for crusted plots which were subjected to simulated rainfall for two hours and then tested in a dry conditions at later date. Many investigators reported that the infiltration rate increased with increasing crop cover. Steichan et al (1979) concluded that depending on the tillage treatments, surface cover increased infiltration rate from 88% to 248% over the uncovered condition.

Morin and Benyamini (1977) concluded that raindrop impact destroys the surface aggregates of bare soils, and gradually forms a continuous crust. The major factor causing reduction of the infiltration rate with time under the conditions of their experiment, was crust formation rather than a reduction of hydraulic gradients in the soil water regime. Moore (1980) demonstrated the effect of surface sealing on infiltration by using numerical solution to Richard's equation. He considered three conditions : of no surface seal, transient surface seal, and steady state surface seal. Also, Moore (1980) showed the surface sealing can have a significant impact on infiltration, and that many of the effects attributed to air entrapment can be explained by surface seal formation, and concluded that continued neglect of this phenomenon in infiltration research will limit the usefulness of research results and limit the advance of the state of art. However, Ghadiri and Payne (1977, 1986) used a high speed cine photography in their study of falling raindrop on unprotected soil surface. They concluded that the kinetic energy of falling raindrops were not the most important factor in bringing about rain erosion, and that the erosive power of raindrops is much higher than suggested by kinetic energy, and there is no non-erosive rain as has been claimed

Levine (1952) reported that increasing the size of the raindrops markedly increased aggregate breakdown. Busch(1973) investigated the interrelationship between sprinkler intensity and soil crusting. He showed that lower sprinkler intensities produced a weaker crusts, and increasing the number of water application cycles did not show a consistent effect on crust strength. Mental and Goldberg (1966), Mohammed and Kohl (1987) studied the effect of water application rate on soil structure. They concluded that as the application rate increased there was a significant reduction in air permeability of the crust. Keller

(1970) studied the effect of sprinkler intensity on soil tilth, and found that soil tilth can be destroyed by high application rates especially in conjunction with long application periods. James (1981) derived an equation that relates kinetic energy to application rate, exposure (irrigation) time, application depth, and the vertical velocity at impact of a characteristic droplet size. Willardson et al (1974) found that short duration -high frequency water applications caused less damage to the soil structure than long duration -low frequency applications on a silty clay soil. Ragab (1983) developed a relationship between time of ponding (Tpo), and the diameter of the droplet (d) on a clay soil for a fixed sprinkler intensity (R), and falling distance (Zf). This relationship is :-

$$Tpo = 390.91\,(R)^{-1.738} \cdot (d)^{-0.124} \cdot (Zf)^{-0.786} \quad \ldots \quad (2.5)$$

Ragab (1983) concluded that the time of ponding is inversely proportional to the drop size of the sprinkler rain. Thompson and James (1983) reported similar results. The depth of water which infiltrated prior to surface ponding for a given application rate was found to increase as the kinetic energy/area per droplet decreased for different application rates. Kelso and Gilley (1983) designed a system for measuring infiltration under center pivot irrigation systems. They used high and low pressure sprinklers and spray nozzles. They found that the infiltration rate was very high under the high application rate spray nozzles approaching 200 mm/hr just after the time of surface saturation, while the infiltration for low application rate impact sprinklers was generally less than 38 mm/hr. They also reported that the amount of water intercepted by the corn crop cover was found to vary widely in response to sprinkler types and meteorological conditions.

2.6.2 Infiltration Equations

Generally, the available techniques suggested to treat the problem of irrigation infiltration may be divided into three general categories. Empirical, physically-based, and numerical. In each category different approaches are made to calculate the infiltration rate, and each method has advantages and disadvantages. The most popular is the empirical technique, because it can be used practically in the field. The most common empirical equation is the Kostiakov equation, which is a simple power function. It takes the form:

$$I = k\,t^{-nl} \quad \ldots\ldots \quad (2.6)$$

Where:

I = infiltration rate (mm/hr.)
t = time of infiltration (hr.)
k and nl are empirical constants

This equation is very popular in irrigation engineering, and it has proved to be very useful equation. It is relatively easy to determine the values of the two constants. The constants evaluated are empirical and have no significant physical interpretation (Clemmens 1983). Fok (1985) used the Fok-power infiltration equation to explain the physical meanings of the k, nl constants. He concluded that the constants have physical meanings related to soil properties and duration of infiltration time. Over short time periods, this type of equation seems to reasonably fit the infiltration data for many soils. However, for long time periods, the resulting infiltration rate using the equation approaches zero, while the actual infiltration rate approaches a constant value usually abcve zero. Another modification for this equation is that the infiltration rate under sprinkler irrigation is higher than the predicted, because this equation was developed under flooding condition. Kincaid et al (1969) monitored the soil water content under a center pivot sprinkler systems under, which surface runoff was observed. The soil water content was monitored during the irrigation season at high points, points of maximum slope, and in low points of the irrigated field. At the same time, a cylinder infiltrometers data were obtained under the center pivot sprinkler systems. They introduced the concept of modified potential infiltration rate, as shown in figure 2.9. The potential infiltration rate (Im)is calculated by this equation:-

$$Im = I \; DP/Da \quad . \; . \; . \; . \; . \quad (2.7)$$

in which:

$$DP = \int_0^t I \, dT$$

$$Da = R \; t$$

Where DP and Da represent the potential and actual cumulative depths of infiltration in the soil, respectively. Kincaid et al (1969) suggested the following equation for the infiltration rate (Ip) after ponding :

$$Ip = k(\; t - \Delta T \;)^{-nl} \quad . \; . \; . \; . \; . \; . \quad (2.8)$$

Where ΔT is the time difference between the cylinder infiltration curve and the intersection of the modified curve with the application rate curve at the same infiltration rate, as shown in figure 2.9. It was first pointed out by Rubin (1966) that the decreasing infiltration rate under constant rate water application is not the same as that obtained when surface ponding

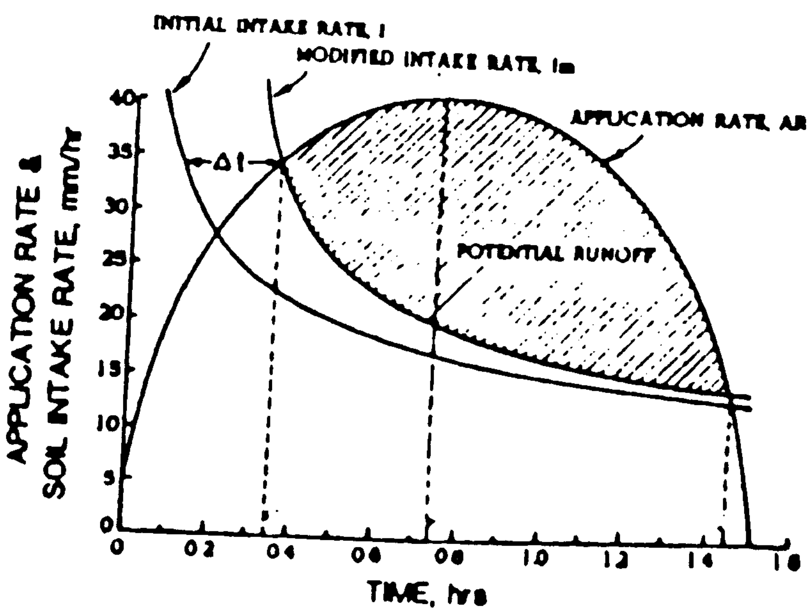


Figure 2.9 Example application rate, soil intake rates, and potential runoff of center pivot systems (after Gilley 1984).

is imposed from t=0 onward. Swartzendruber and Hillel (1975) proposed an equation under constant application rate, which is similar to the modified kostiakov's equation. This equation is :

$$I = k\, t^{-n1} + C \quad . \quad . \quad . \quad . \quad . \quad (2.9)$$

where:

C is equal to the final infiltration rate.

The final infiltration rate is added to the equation at all times, thus the final infiltration rate approaches this value. As pointed out by Ghosh (1980) this modified kostiakov equation is similar in form to both the Philip and kostiakov equations. This type of equation has been used to describe the infiltration under all types of irrigation systems including center-pivot systems, Kincaid et al (1969). The American soil conservation service has classified soils into infiltration families using a modification of kostiakov's equation as a basis, Slack (1978).

Thus as pointed out by many researchers that the modified Kostiakov is more suitable under sprinkler irrigation, therefore it will be used in this study.

2.7 SOIL EROSION

Soil erosion is a work process in the physical sense that work is the expendure of energy, and energy is used in all the phases of erosion in breaking down soil aggregates, in splashing them in the air, in causing turbulence in surface runoff, in scouring and carrying away soil particles, Hudson (1981). The amount of soil erosion by water depends basically upon the combination of the power of the rain to cause erosion and the ability of the soil to withstand the rain. In a mathematical terms erosion (E) is a function of the rain erosivity (R), and of the soil erodibility (K) :

$$E = f(R,K)$$

Other factors certainly influence this basic relationship, reducing or increasing rain erosivity and soil erodibility and consequently, soil erosion rate.

The erosion process has an important influence on both infiltration and surface runoff because they alter the soil physical properties of the soil surface, (Ellison 1947). Raindrop impact detached soil particles, breaking down soil clods and aggregates thereby, reducing the random roughness and surface storage capacity of the soil, Moore et al (1980). This will lead to sealing of the soil surface and hence to lower infiltration and increased runoff, and this may further increase soil erosion. In experiments with simulated rainfall and runoff on soil beds, Young and Wiersma (1973) reported that splash accounted for an average of 14% of soil loss from a surface between rills, while combined flow plus splash accounted for 86% of soil loss. Singer and Walker (1983) found that when rainfall or rainfall plus runoff were applied soil erosion was greatly increased and that was due to the high detaching and transporting power of raindrops impacting shallow runoff water layers.

So the rainfall application rate will be one of the dominant factors which influence the rate of soil erosion. Rainsplash is the most important detaching agent, Morgan (1980). There is a great deal of experimental evidence to suggest a link between the erosive power and the mass and velocity of falling drops. Many investigators have studied the role of falling rain on splash erosion, such as Ellison (1944), Mihara (1951), Bisal (1960), and Free (1960).

Several experimental studies have established relationships between soil splash and intensity (Moldenhouer and Long 1964; Bubenzer and Jones 1971, and Meyer 1981). The experimental evidence therefore, suggests that rainfall intensity and energy are likely to be closely linked with erosivity. Willardson et al (1974) found that short duration-high frequency water application caused less loss of soil structure than long duration-low frequency water applications on a silty clay soil.

The other important factor which affects soil erosion is slope of the land. The potential energy of surface runoff on sloping land may equal or exceed that of the rain, depending on the length and steepness of the slope and the amount of surface runoff. Many investigators have studied the effect of the slope on erosion, such as Meyer and Kramer (1969); D'souza and Morgan (1976); Young and Mutchler (1969); Foster and Wischmeier (1974); Mutchler and Greer (1980), and Evett and Dutt (1985).

Relatively little research has been conducted to evaluate soil losses from rainstorms on land with bedded or ridged rows, Although several studies have shown serious soil losses can occur even on nearly flat bedded land (Bernet et al 1978, and Murphree and Mutchler 1980). Bedded rows may result in greater losses than unbedded rows (Mutchler and Murphree 1981), but bedded rows with graded furrows can reduce losses from land of moderate slope (Richardson et al 1969; Harris and Watson 1971). Some research has evaluated soil erosion, resulting from furrow irrigation (Berg and Carter 1980).

So, there is obviously an association between the amount of soil erosion and the amount of rainfall, and the steepness of the slope. Erosion would be expected to increase with increase in slope steepness as a result of increasing the velocity and volume of surface runoff. There are several ways to reduce soil erosion and that can be done by ways of increasing soil infiltration rate and reducing runoff. Pitting or diking implements have been developed to increase infiltration and surface storage. These tillage methods were developed to reduce runoff problems in areas irrigated with low pressure irrigation systems. Also crop residue and crop canopy have long been used to reduce runoff and soil erosion. The major role of soil cover is in interception of raindrops so, that raindrop impact is dissipated by the soil cover rather than imparted to the soil surface. Therefore, reducing soil erosion is possible with low pressure irrigation systems.

2.8 SAVING ENERGY

Energy saving resulting from the use of low pressure sprinkler irrigation systems may be an important consideration in many areas. In general, it can be said that a reduction in nozzle pressure produces a reduction in pumping costs, but this may also cause an increase in surface runoff and a reduction in field efficiency. Gilley and Mielke (1980) presented an approach which can be used to estimate energy savings between two irrigation systems. The mathematical representation of the method is as follows:

$$Pes = 100(1-Dn2/Dn1.Ht2/Ht1.Ei1/Ei2) \quad . \quad . \quad . \quad . \quad . \quad (2.10)$$

where:

Pes = the energy savings resulting from the low pressure (%)
Dn = net depth of water (mm)
Ht = the total dynamic head of the system (M)
Ei = irrigation efficiency

subscript 1 indicate initial values and subscript 2 indicate values after pressure reduction. It is assuming that pumping plant is operating at a constant efficiency. Gilley and Watts (1977) made a comprehensive study of how to save energy in irrigated agriculture and described a variety of irrigation systems. They also, reported a relationship for the amount of energy required to pump water, as follows:

$$PE = (cf\ A\ Dn\ Ht)/Ei \quad . \quad . \quad . \quad . \quad . \quad (2.11)$$

where:

PE = the pumping energy required (megajoules)
A = irrigated area (ha)
Dn = the net depth of water applied (mm)
Ht = the total dynamic head on the system (m)
Ei = the irrigation efficiency, or the fraction of the water pumped, that is stored in the root zone .
cf = conversion factor

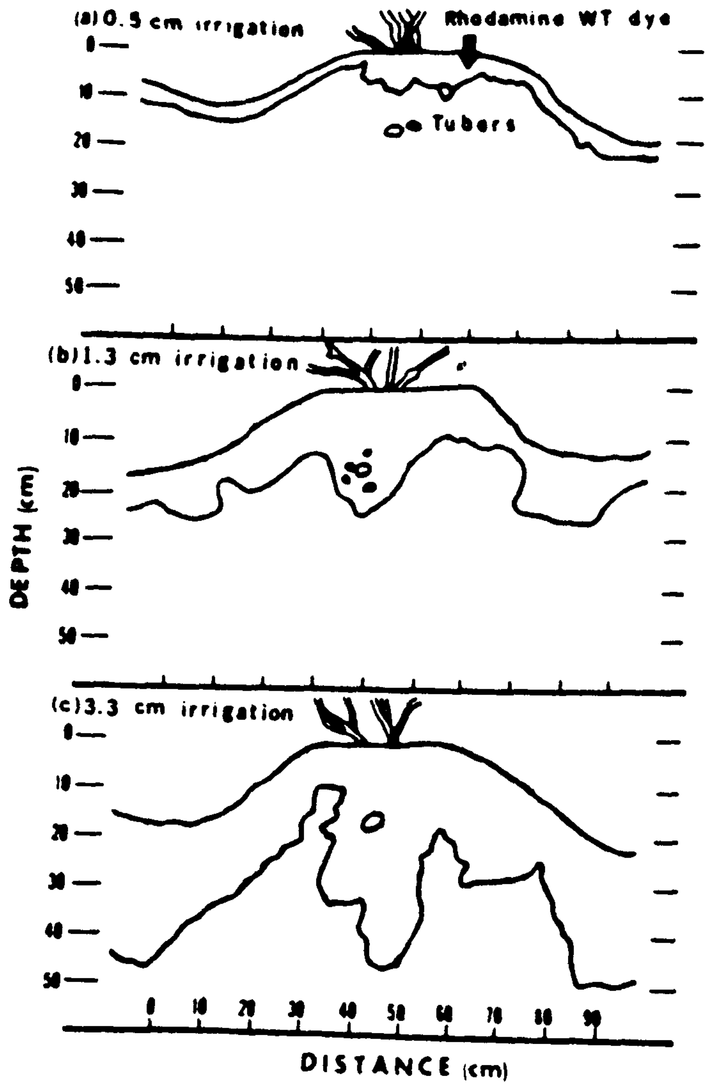
Gilley and Watts (1977) suggested that the final energy savings may result from a tradeoff between the savings obtained with a lowering of pressure and a larger water requirement due to reduction in the irrigation efficiency. Nir et al (1980) conducted an experiment on a self propelled irrigation system at very low pressure (47 to 100 kpa). They concluded that there was saving of energy and water. Reardon (1979) reported that with low pressure center pivot systems operating at 138 kpa (20 ib/in2) and high pressure center pivot systems operating at 414 kpa (60 ib/in2) there can be upto 35-40% on energy saving with a good irrigation efficiency by using the low pressure system. James and Blair (1984) compared the performance of five different low pressure center pivot applicators systems to each other and to that of a system with conventional high pressure impact sprinklers with upward sloping terrain (2-5%). They found that considering all terrain, the system with low pressure impact sprinklers used approximately 82%, and the system with fixed spray nozzles used about 68% of the energy used by the system with conventional high pressure impact sprinklers. Gilley and Watts (1977) reported that water savings in the region of 20% were possible with low pressure center pivot irrigation systems.

Reardon (1979) compared low pressure and high pressure irrigation systems on area of 55.4 hectares (137 acres). He showed that the total estimated energy savings is estimated at about 19 million killowatt hour / year. A possible saving to the consumer of $384,840.0 per year in Montana in the U.S.A. by using the low pressure irrigation system. Gilley and Mielke (1980) concluded that a lowering of the irrigation efficiency is common with low pressure sprinkler systems. They also produced some curves to determine the irrigation efficiency with different lowering pressures. Lyle (1983) reported that discharging water at very low pressure with LEPA system a potential energy saving exists over sprinkler method. Buckingham (1980) concluded that low pressure irrigation can under most conditions help to reduce the energy demands of irrigation and increase crop production efficiency. Gilley and Supalla (1983) examined through various cost equations the economic benefits from seven energy saving practices in irrigation. The practices involved pumping plant adjustments, irrigation scheduling, and improved irrigation efficiency for both gated pipe and center-pivot systems, low pressure center-pivot irrigation system was also examined, with shallow lift (8 m) and low net irrigation applications (33 cm), the only economic energy saving practice for gated pipe irrigation involved pump performance. With high lift (75 m) irrigation scheduling also become economic with center-pivot irrigation, by far the greatest energy saving resulted from low water distribution pressure (from 550 to 250 kpa).

2.9 SOIL WATER DISTRIBUTION

Interception of irrigation by the plant canopy and stemflow resulting in non-uniform distribution of irrigation beneath the canopy has long been recognized in forest trees (Eschner 1967). Rutter (1975) stated that stemflow may vary from quite small quantities to as much as 20% of net rainfall. Jackson (1975) reported that the stemflow was small amounting to only about 1% of gross rainfall from tropical trees in east africa. Also, the shape of the ridge influences soil water distribution within it. The results of Kouwenhoven (1978) showed that a flat topped ridge had higher soil moisture content at its centre than one with a sharp peak.

There have been few studies of the distribution of water irrigation beneath the plant canopies of agricultural crops despite the implications which non-uniform distribution might have for studies of crop water and nutrients. Saffigna et al (1976) traced the patterns of infiltration of rainfall and irrigation under potato canopies, and demonstrated that stemflow funnelled water into localized areas around the stems. They found that from 20 to 46% of the irrigation and from 4 to 23% of the rainfall on the canopy flowed down the stems. Figure 2.10 shows the variation of wetting depth with different irrigation



Figur 2.10 Distribution of Rhodamine WT under 49-day-old potato plants 1 day after sprinkler irrigation (after Saffigna et al 1976).

water amount. That relatively dry areas occurred beneath the ridge, and the main water flows were directly below the plant and beneath the furrow as the amount of irrigation increased. Prestt (1983) found that more water was concentrated either in the centre of the ridge beneath the stem or below the furrow. Appelman et al (1980) found that the amount of water intercepted by sugar-beet was a function of rainfall intensity, when the rainfall intensity is 27.5mm/hr the interception was 3.6%, but the interception was 15.9% when the intensity was 5.8 mm/hr. Morgan et al (1986) have reported that the stemflow was 1.5 to 4.35% from a potato crop with crop cover 3.75 to 23.85%, and the leaf drip accounted for about 20% of rainfall reaching the ground. Jefferries and MaCkerron (1985) measured the stemflow of potato crop at irrigation intensity of 10 to 124 mm/hr, they found that the stemflow varied from 17 to 87% of the rainfall falling on the crop.

2.10 CONCLUSION

In recent years much attention has ben given to more efficient irrigation as means for saving water and energy. There is no doubt in the literature that significant energy saving can be made by a decrease in the operating pressure of sprinkler irrigation systems. There are several types of spray nozzles available for use on low pressure irrigation; however these low pressure devices have the disadvantage of increased water application rates. The high rate of water application increases the potential runoff of water applied. This may restrict their use to certain topographies, soil types, or tillage and crop-management systems, depending on slope and type of soil. Runoff water may cause soil erosion and increase soil losses, and therefore, low irrigation efficiency. Most of the researchers in the literature agreed that the runoff problem is the major problem associated with this system.

Therefore, there is a need to examine the relationship between the water application method, the application rate, soil cultivation practices, and the crop being irrigated. A mathematical model for low pressure irrigation systems so that runoff under different low pressure devices with different application rates, different cultivation practices, and crops can be determined asabasis for system design. This may lead to predict quantitatively to what extent the problems might be amenable to various control measures.

CHAPTER 3
SELECTION OF RUNOFF MODEL

3.1 INTRODUCTION

The purpose of this chapter is to review the available rainfall-runoff models with the purpose of selecting the most appropriate one that could be adapted to the requirements of this study for predicting surface runoff from a simple micro-catchment during irrigation. The selected model should be capable of simulating the runoff and yet be simple enough to be applied to practical situations relating to sprinkler irrigation practice.

3.2 SURFACE RUNOFF PROCESS

Assuming a constant rainfall/irrigation rate, the hydrograph shown in figure (3.1) is a graphical representation of the surface runoff process. Assuming rainfall rate exceeds the interception rate, infiltration begins immediately with the beginning of rainfall. In general, no other process will begin until the sum of the rates of the infiltration and interception decrease below the rainfall rate, at which time the depression storage requirements begin to be filled. The chief component of depression storage is the filling of the deepest depressional areas. At some depression storage the surface runoff begins. An equation relating the principle component for the runoff process can be developed from the continuity and momentum equations.

The basic components of the runoff process from a simple

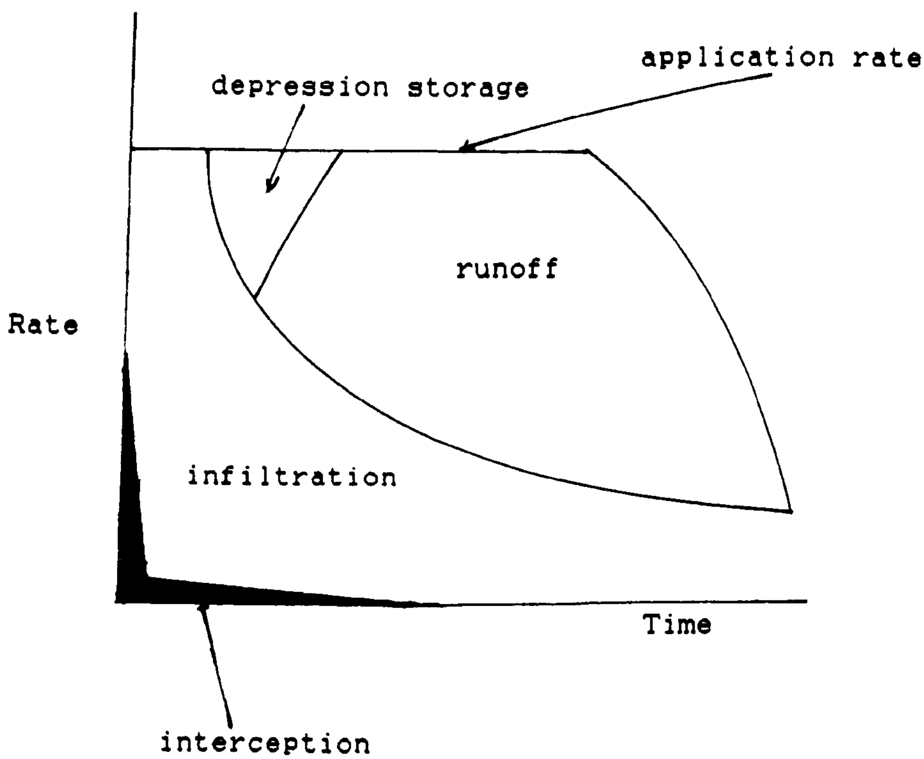


Figure 3.1 Graphical representation of surface runoff process (after Huggins and Monke 1966).

catchment ignoring plant interception and depression storage are shown in figure 3.2. Surface runoff over a catchment is known to follow certain laws of physics : 1- law of conservation of mass (continuity) and, 2- law of conservation of momentum. These governing equations of motion for gradually varied unsteady flow over a plane are derived by applying the these laws. The equations which obey these laws can be written in the following form (Rovey et al 1977). The one dimensional continuity equation with lateral outflow can be witten as

$$d(Vh)/dx + dh/dt = Rx(X,t) \quad . \quad . \quad . \quad . \quad . \quad (3.1)$$

The momentum equation for one dimensional gradually varied unsteady flow can be written as :

$$1/g(dV/dt+VdV/dx)+dh/dx = S - Sf - Rx/gV/h \quad . \quad . \quad . \quad (3.2)$$

where :

h = depth of flow
V = flow velocity
X = distance
t = time
Rx = rainfall excess
Sf = friction slope
g = acceleration due to gravity
S = plane slope

Numerous investigators have studied surface runoff from various standpoints; ranging from almost a pure empirical approach to a complete mathematical analysis of the equations that model the process.

Kinematic wave theory produces an adequate physical and mathematical representation of surface runoff, and the kinematic wave equations are a common choice in the simulation of flow over catchments. The equations are well established and generally

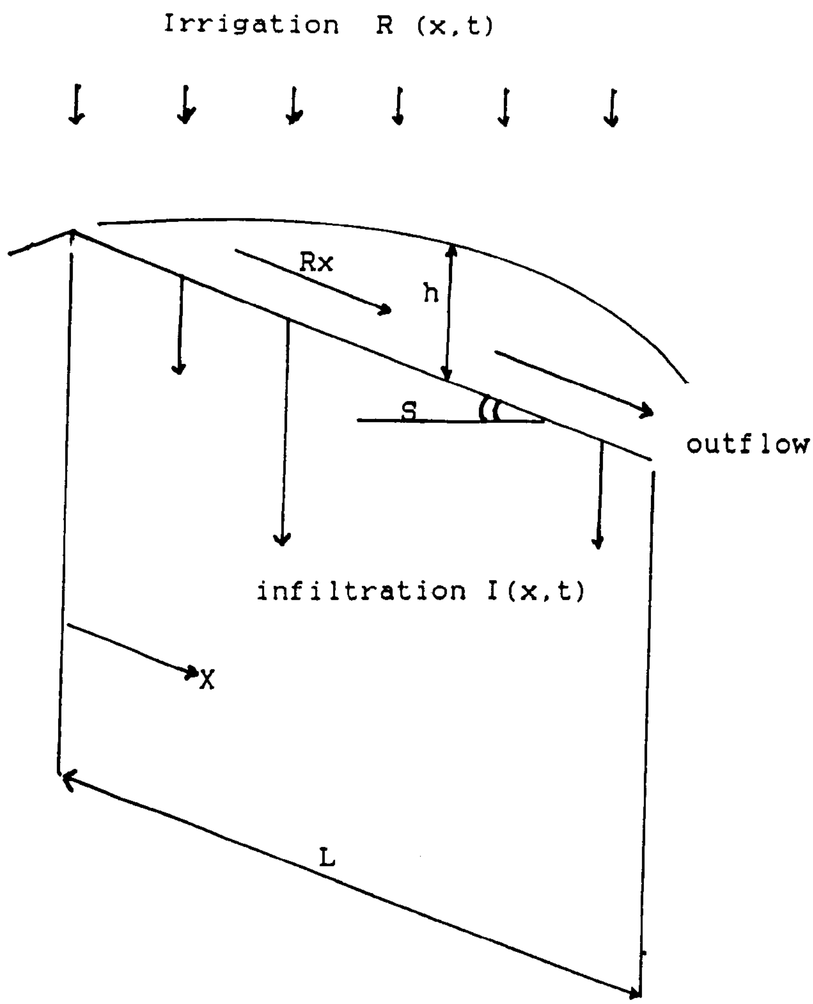


Figure 3.2 Definition sketch of surface runoff on a plane (after Woolhizer 1975).

lead to physically realistic solutions without the computational complexities that usually plague full dynamic wave formulations, Ponce (1986). The kinematic wave equations for surface flow are shown to be widely applicable to overland flow problems, Eagleson (1970).

3.3 KINEMATIC WAVE THEORY

The continuity and momentum equations for gradually varied unsteady flow were developed by Saint Venant in 1871 (Yevjevich 1960). Direct solution of these equations, even by numerical means was not possible before electronic computers were available except for very simplified initial and boundary conditions (Rovey et al 1977). Graphical methods were used for approximate solutions but even these were tedious. Usually simplified methods considering only continuity or approximations to the momentum equation were used to route flows (Yevjevich and Barns 1970).

Many investigators have studied gradually varied unsteady flow and found conditions for which a simplification of the complete momentum and the continuity equations are sufficiently accurate. Lighthill and Whitham (1955) introduced the kinematic wave theory, and utilized it in describing flood movement in long rivers. They also developed kinematic wave equations for overland flow. In their general treatment of the theory, it was suggested that the solution could be found by numerical integration along the characteristics when the inflow was a function of time and distance. An explicit solution could be found for the lateral inflow being constant or a function of distance only. A variety of factors influencing the stage-discharge relation were considered. The application of the theory to the determination of flood movement was demonstrated.

Iwagaki (1955) developed an approximate method of characteristics for unsteady flow in open channels of any cross-sectional shape, and proposed that the method would be applicable to hydraulic analysis of runoff estimation in actual rivers. The kinematic assumption was implicitly utilized in the analysis. The lateral inflow was taken nearly uniform. The agreement between the results of the method and the experiments was reported to be good.

These investigators laid down the foundation, developed the mathematical base, and demonstrated the applicability of the kinematic wave theory. However, the application was limited to describing flood movements in rivers and channels only. No attempt was made to utilize the theory in catchment hydrology until Henderson and Wooding (1964). They used it in treating the hydrograph from a steady rain of finite duration for laminar or turbulent flow over a sloping plane, neglecting the water surface relative to the slope of the plane. The relationship developed showed certain distinct differences from those postulated in the unit hydrograph method (Nash 1957, and Dooge 1959). A comparison made between the results of calculations and those of experimental measurements, was found to be reasonably good. The kinematic wave solution was also compared with the solution to the problem embodying groundwater flow by Henderson and Wooding (1964) through a porous medium overlying a sloping impermeable stratum; significant differences were noted between the two.

Wooding (1965a, 1965b, 1966) employed the kinematic wave theory in the development of a 2-component, 4-parameter model for a v-shaped catchment (two planes contributing runoff to a channel between them). Analytical and numerical solutions were presented, and numerical solutions were compared with measurements from the natural catchment. All catchments, regardless of their complexity, were represented as a single v-shaped catchment with overland flow planes contributing lateral inflow to a channel in the apex of the V. In spite of good agreement reported between observed and computed hydrographs, it was concluded that a better geometrical description of the stream network was desirable. One feature of the hydrograph that the model was unable to produce was the steeply rising portion of the hydrograph caused by concentration of runoff.

Since Wooding, numerous attempts have been made to apply the kinematic wave approximation to modeling catchment surface runoff response. Some of the more notable contributions will be reviewed here. In spite of a successful attempt by Wooding some questions remained unresolved. They were for example: what is the criterion for the choice between the complete equations and the kinematic approximation of motion ? what degree of approximation is introduced in the solution by the kinematic wave approximation ? how good is the kinematic approximation in hydrologic problems as opposed to the complete equations?.

Woolhizer and Liggett (1967) solved equations for overland flow, in three non-dimensional forms, for the rising hydrograph by using finite difference techniques. A single dimensionless parameter was found to delineate a criterion for choice between the complete equations and the kinematic approximation. It was shown that for most hydrologically significant cases, the kinematic wave solution would give accurate results. A similar conclusion was reached by Overton (1972) when he analyzed more than 200 overland flow hydrographs generated by simulated rainfall on long impermeable planes. It was shown that kinematic waves prevailed over dynamic waves. It was also observed that most flows appeared to be either in the transition from laminar to turbulent state, or in a fully developed turbulent state. The transition was significantly found to be affected by rainfall intensity. However, error involved in treating all flows as turbulent would be small with resulting analysis made considerably less complex.

Overton and Brakensiek (1970) used a kinematic model similar to the one by Wooding (1965a). The solution of the catchment hydrograph for a steady rainfall excess rate of a long duration was shown in general dimensionlized form in terms of the physical and hydraulic characteristics of the overland flow plane and the stream channel. The results were compared to demonstrate the effects that errors in model parameters had on the computed outflow. The results were used to simulate a relation between storm lag time and rainfall excess rate. In another attempt, Brakensiek (1966) gave a formal definition of kinematic flood routing and its application. The method utilized the full equation of continuity and did not require the use of a relationship between reach storage and flow. The solution was obtained by numerical approximation. Three different approximations for the continuity equation were considered, and their stability was examined with regard to error growth taking place in each scheme. The method did not require the subjective coefficients used to relate reach storage to out flow. Its feasibility was indicated for the computational system for predicting hydrographs. A technique was given by which one-dimensional variations (e.g. with elevation) could be introduced into hydrologic computations.

In the preceding attempts, a v-shaped geometry, proposed by Wooding (1965a) was taken to represent the natural catchment. Some dissatisfaction was expressed by wooding himself with regard to the inadequacy of the proposed geometrical representaion of a natural catchment. Investigators continued to use it for its simplicity until Brakensiek (1967) came up with the concept of the kinematic cascade. He utilized this notion in the transformation of the upland catchment into a cascade of planes discharging into a single channel. The kinematic cascade concept has since been incorporated in numerous studies. Woolhiser et al (1970) used this concept to describe overland flow and channel flow for small rangeland catchment. The friction relation was assumed to be of the Darcy-Weisbach form, with initially laminar flow becoming turbulent flow at transitional Reynolds-number of 300. Kibler and Woolhiser (1972) developed dimensionless equations for a kinematic cascade, and derived general equations for a single element in the cascade. Properties of the solution for a kinematic cascade with pulsed lateral inputs were examined.

Woolhiser (1969) suggested that a catchment consisting of a v-shaped section plus a portion of the surface of a cone at the upstream end might result in a better description than the simple v-shaped catchment. Because of the concentration of flow in the cone such a model could be taken to represent a catchment of any complexity or it could be used as a basic element in a network model. The kinematic wave equation for an experimental converging surface was solved numerically for a number of values of the convergence parameter. An analytical solution was given for recession from equilibrium. He found for pulse inputs of lateral inflow that the shape of the hydrograph might be changed appreciably by varying the convergence parameter.

In order to test the utility of such a model, Woolhiser et al (1971) presented experimental data for two types of surfaces from a converging overland flow section, and compared the properties of the experimental hydrographs with those predicted by kinematic wave theory. Chezy's friction law, and both laminar and turbulent regimes were used. Overton (1971) showed hydraulic solutions of lag time for idealistic surfaces using the kinematic wave equations. The surfaces included (1)uniform plane, (2) hill slope as cascade of planes, (3) v-shaped catchment, (4) v-shaped catchment with hillslope, (5) converging section, (6) concave surface. Lag time were shown to be related to roughness and catchment slope, and the input rate. Langford and Turner (1973) simulated rainfall on a stabilized fallow surface with a friction relationship in the form of laminar-turbulent Manning's n that varied with rainfall intensity. The surface retention showed a hysteresis effect because of change of hydraulic roughness under condition of rain and no rain.

In all of the preceding investigations very little attention was paid to the variability in rainfall and catchment characteristics. Along this line Eagleson (1970) used the kinematic wave equation model by wooding for the determination of peak discharge from an impulse of rainfall excess located at any distance from the catchment outlet. Foster et al (1968) used the kinematic wave theory in formulating a model for predicting overland flow on rough, short slopes. They analysed the field hydrographs from fallow erosion study plots with retention storage and coefficient friction factors. These results were used in a model to simulate hydrographs, and compared with field hydrogrphs, which showed a good agreement between the data. Smith and Woolhiser (1971) combined the kinematic wave equation for unsteady overland flow on cascaded planes with mathematical model of infiltration based on the partial differential equation for vertical, one-phase, unsaturated flow in soils. They compared the predicted results with the field data, and the agreement was found adequate. Singh (1975) developed a formulation of kinematic wave models of catchment runoff called hybrid approach which is part numerical and part analytical. He demonstrated that by applying it to a set of rainfall-runoff events on natural catchment, and concluded that this approach is more efficient computationally than totally a numerically approach. Singh and Buapeng (1975) compared four methods of determining rainfall-excess by using ϕ-index and equations of Horton, Kostiakov and Philip. They utilized these methods in a non-linear kinematic wave model to predict surface runoff from two natural catchments. They concluded that accurate determination of rainfall excess is crucial to runoff prediction, of the four methods considered. Horton equation was the best; equation of philip and Kostiakov were comparable, and ϕ-index grossly misrepresented rainfall excess, and that errors in hydrographs computation can be reduced considerably by the use of more re-modified method of infiltration.

Li et al (1975) developed a numerical model for kinematic wave problem, which allows unsteady, non-uniform lateral inflow. They concluded that the numerical solution agree very well with analytical model. Rovery et al (1977) developed a finite difference solution to the kinematic wave problem with Horton's infiltration equation to compute flows in channels of circular cross-section for routing through storm rain. Lane et al (1975) studied the simplifications in catchment geometry in simulation of surface runoff. Cundy and Tento (1985) developed a solution to the kinematic wave equation for overland flow, where lateral inflow determined from constant rainfall, and philip infiltration equation was used.

The comparison between the kinematic wave method and the diffusion method was investigated by a number of researchers. Ponce et al (1978) used a linear stability analysis of shallow water equations to examine the applicability of kinematic and diffusion models in open channel flow. They concluded that most overland flow problems can be modelled as kinematic flow. Markb and Woolhiser (1980) reported a comparison of solution of shallow water equation for unsteady one dimensional flow over a plane and solution of the diffusion and kinematic wave equations. Ponce (1986) formulated a diffusion wave method for catchment dynamics and compared with kinematic wave method. He concluded that the diffusion wave method has better convergence properties than the kinematic wave method.

Solutions for the surface runoff-infiltration problem investigated by the use of physically-based theoretically studies indicated that overland flow rates are affected by the basin surface and subsurface characteristics, and the antecedent soil moisture conditions(Mein and Larson 1971, Yen and Akan 1983, Akan and Yen 1981, 1984, and Akan 1985). Also the distribution of rainfall intensity is an important factor(Yen and Chow 1980).

3.4 SOLUTION FOR THE KINEMATIC WAVE EQUATIONS

It is desirable to know before a problem is analysed, whether the kinematic wave method will give reasonable results. Woolhizer and Liggett (1967) in a thorough analysis using the method of characteristics and nondimensional form of the continuity and momentum equations showed that when the kinematic wave number (k) was above 10, the kinematic wave method will be a good approximation to the de Saint Venant equations. Kinematic wave number is defined by :

$$K = S \quad L / Hn\ Fo \quad . \quad . \quad . \quad . \quad . \qquad (3.3)$$

where

K = kinematic wave number
S = plane slope
L = length of flow plane
Hn = normal depth at the downstream end for the discharge at equilibrium
Fo = froude number
$Fo = Vo / (g.Hn)^{0.5}$
Vo = normal velocity at the downstream end for the discharge at equilibrium

Figure (3.3) shows that for k > 10, the kinematic wave solution labelled k = ∞ is a good approximation. The kinematic wave number is often several thousands or more for many cases of runoff flow (Rovey et al 1977). Kinematic wave methods have usually been used to simulate runoff from catchment on large scales, but some work has been conducted on relatively small catchments. These catchments were either agricultural or urban areas.

The kinematic wave theory can be solved by two ways, analytically or numerically. The development of the surface runoff model will however, require a description of catchment

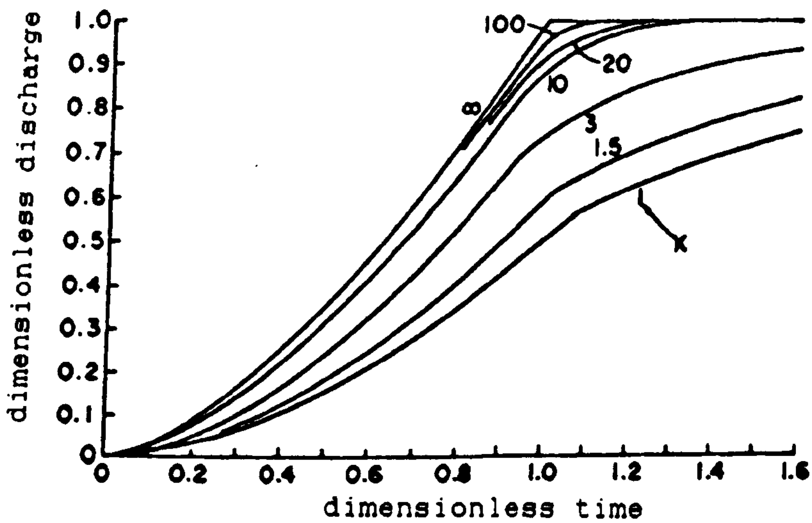


Figure 3.3 Variation of dimensionless hydrograph with kinematic wave number (K) (after Woolhizer and Ligget 1967).

geometry, lateral inflow, rainfall and, infiltration rates. With these points in mind the selection of the most appropriate of these approaches to describe the surface runoff process is required.

3.4.1 Analytical Approach

The analytical approach can be used in determining the surface runoff by using the kinematic-momentum equation. It is assumed that the values of α and D are constants and, the input is invariant in time and space.

Since the analytical solutions are feasible only when the input is invariant in time and space (Singh 1975). So, it is desirable to attempt a more realistic analysis of surface runoff to take into consideration all the points mentioned in the model selection and this may indicate a numerical approach as as being more appropriate.

3.4.2 Numerical Approach

The mathematical alternative to analytical solution is the numerical approach. The kinematic wave equations can be solved analytically for many initial and boundary conditions. Such solutions became cubersome for realistic solution, so it is convenient to use a numerical solution (Rovey et al 1977). Methods for the numerical solution of the set of equations of nonsteady flow in wide open channels may be appropriately classified as :

1) direct methods; and
2) characteristic methods.

In the direct methods, the finite difference representation is based directly on the primary equations. In the characteristic methods, the equations are first transformed into their characteristic form, which is then used to develop the finite difference representation. In the direct methods a fixed mesh of points on the time-distance plane is commonly employed to identify grid points. In the characteristic methods, solution may be obtained at the intersection of the characteristic curves on the time-distance plane or at fixed points of a rectangular mesh by interpolation.

The finite difference scheme used in direct and characteristic methods may be classified further into explicit and implicit methods. In the explicit methods, the finite difference equations are usually linear algebraic equations from which the unknowns can be evaluated explicitly a few at a time. In the implicit methods, the finite difference equations are generally nonlinear algebraic equations in which the unknowns occur implicitly.

Applications of various numerical methods to unsteady flow problems and the shortcomings of the various methods can be found in the literature. For example, the method of characteristics using the characteristic network is inconvenient for irregular shapes because the shape cross sections are surveyed at fixed locations. The direct explicit method, commonly known as the explicit method, requires very short computation time steps because of a stringent stability condition. That has led to the development of the implicit method. A four-point implicit method which has the advantages of economy of computer time and accuracy and stability under a wide range of time increments, was used by

Quinn and Wylie (1972), and Fread (1973). Kibler and Woolhizer (1970) investigated several different methods of numerical solutions including : (1) an upstream differencing scheme, (2) a four-point implicit scheme, and (3) the Lax-Wendroff explicit scheme. These finite difference schemes (table 3.1) were compared with the method of characteristics for evaluation of their performance. They found that the Lax-Wendroff and the four-point methods gave the most satisfactory results. The Lax-Wendroff method has second order accuracy but because it is explicit, it requires a limitation of the time step size to maintain numerical stability. The implicit four-point method is unconditionally stable and so it may save some computation time if larger time steps are used. However, the finite difference equation must be solved by an iterative technique. If convergence of this iterative scheme is slow the advantage of unconditional stability may be only apparent (Woolhizer 1975). In a comparative analysis of four numerical methods, Price (1974) found that the four-point implicit was the most efficient and maintained stability under severe test conditions.

In view of the advantages of the numerical approach it was proposed to use this method with the four-point implicit finite difference approach, this involves modelling the flow region as a grid or a mesh of points, called nodes separated from each other by finite difference called the mesh or space increment. A solution is obtained by starting at certain boundaries with known conditions, and along the entire mesh to other boundries of known conditions and sweeping across the entire mesh to the other boundries of known conditions. The solution also depends on time, then this is an additional dimensional which is also

Method	Finite Difference Equation	Order of Approximation	Linear Stability Criterion
Single-Step Lax-Wendroff	$h_j^{i+1} = h_j^i - \Delta t \frac{k}{n}\left[\frac{\left({h_{j+1}^{i}}^N - {h_{j-1}^{i}}^N\right)}{2\Delta x} - \frac{1}{2}\left(q_{j+1}^i + q_{j-1}^i\right)\right] + \frac{\Delta t^2 Nk}{4n\Delta x}\left\{\left({h_{j+1}^{i}}^{N-1} + {h_j^i}^{N-1}\right)\left[\frac{k}{n}\frac{\left({h_{j+1}^i}^N - {h_j^i}^N\right)}{\Delta x} - \frac{1}{2}\left(q_{j+1}^i+q_j^i\right)\right] - \left({h_j^i}^{N-1} + {h_{j-1}^i}^{N-1}\right)\left[\frac{k}{n}\frac{\left({h_j^i}^N - {h_{j-1}^i}^N\right)}{\Delta x} - \frac{1}{2}\left(q_j^i + q_{j-1}^i\right)\right] + \frac{2n\Delta x}{Nk\Delta t}\left(q_j^{i+1} - q_j^i\right)\right\}$	$O(\Delta x)^2$	$\frac{\Delta t}{\Delta x} \le \frac{n}{Nk\bar{h}^{N-1}}$
Upstream Differencing	$h_j^{i+1} = h_j^i - \frac{Nk}{n}\frac{\Delta t}{\Delta x}\left({h_j^i}^N - {h_{j-1}^i}^N\right) + q_j^i \Delta t$	$O(\Delta x)$	$\frac{\Delta t}{\Delta x} \le \frac{n}{2.75kNh^{N-1}}$
Brakensiek's Four Point Implicit	$\frac{h_j^{i+1} - h_j^i + h_{j-1}^{i+1} - h_j^i}{2\Delta t} + \frac{k}{n\Delta x}\left({h_j^{i+1}}^N - {h_{j-1}^{i+1}}^N\right) - \frac{1}{4}\left(q_{j-1}^{i+1} + q_j^{i+1} + q_{j-1}^i + q_j^i\right) = 0$	$O(\Delta x)$	Unconditionally stable

Table 3.1 Rectangular grid finite-difference schemes (after Kibler and Woolhizer 1970).

divided into short segments or time increments, and treated in a similar manner. The accuracy of a finite difference model is largely dependent on the size of space and time increments. The use of a numerical solution in surface runoff model requires determination a priori of Δx and Δt, and the input could be variant in space and time (Singh 1974).

3.5 DEVELOPMENT OF KINEMATIC WAVE THEORY

The equations of spatially varied unsteady flow over a plane describe many of the important aspects of runoff. The problem under consideration is shown in figure 3.2. A plane of unit width, length (L), and slope (S), receives rainfall at a rate R(x,t) per unit area, which is a function of distance (X), and time (t). Water is infiltrating at rate I(x,t). The net rate of lateral outflow is

$$Rx(X,t) = R(X,t) - I(X,t) \quad . \quad . \quad . \quad . \quad . \quad (3.4)$$

The Flow is assumed to be one dimensional,and the dependent variables are the mean velocity (V) and mean depth (h) For runoff on a plane as shown in figure 3.1.

Lighthill and Whitman (1955), Henderson (1963), and Woolhizer and Liggett (1967) have reported on conditions where the gravity and friction components dominate the other terms of the momentum equation. These two components reach an approximate equilibrium, so that the momentum equation can be reduced to :

$$S = Sf \quad . \quad . \quad . \quad . \quad . \quad (3.5)$$

This simplification is known as the kinematic wave approximation to the momentum equation (Wu et al 1978).

If the bed slope is constant, the friction slope over the plane must also be constant, then the unit width discharge, and the velocity equations can be written (Rovey et al 1977)) as :

$$q = \alpha h^{D} \quad . . . . . \quad (3.6)$$,and

$$V = \alpha h^{D-1} \quad . . . . . \quad (3.7)$$

where:

q = the discharge per unit width
α = coefficient for overland flow that is related to surface roughness and geometry.
D = exponent for overland flow that is related to flow regime.

Equation (3.6) or (3.7) can be substituted in equation (3.1) to produce a partial differential equation with one dependent variable (Smith and Woolhizer 1971, Woolhizer 1975, and Wu et al 1978) as :

$$dh/dt + \alpha dh^{D}/dx = Rx(X,t) \quad . . . . . \quad (3.8)$$

or

$$dh/dt + D\alpha h^{D-1} \; dh/dx = Rx(X,t) \quad . . . . . \quad (3.9)$$

The total differential of h(X,t) (Smith and Woolhizer 1971, and Lane et al 1975) is :

$$dh = dh/dt \,.dt + dh/dx \,.dx \quad . . . . . \quad (3.10)$$

Equations (3.9) and (3.10) can be solved simultaneously, and the matrix form of the equations is written (Rovey et al 1977) as :

$$\begin{bmatrix} 1 & \alpha D h^{D-1} \\ dt & dx \end{bmatrix} \begin{bmatrix} dh/dt \\ dh/dx \end{bmatrix} \quad \begin{bmatrix} Rx \\ dh \end{bmatrix} \quad . . . . . \quad (3.11)$$

Equating the determinant at the square matrix to zero defines the path of the characteristic.

$$dx/dt = \alpha D h^{D-1} \quad . . . . . . (3.12)$$

Substituting the column vector of the right hand side of equation (3.11) into the second column at the square matrix and equating the determinant to zero defines the rate of change of depth with respect to time along the characteristic.

$$dh/dt = Rx \quad . . . . . . (3.13)$$

Equations (3.12) and (3.13) are the characteristics equations. Equation (3.13) can be integrated for constant Rx to find the depth along the characteristic as :

$$h = ho + Rx\ (t - to) \quad . . . . . (3.14)$$

where ho is the initial depth at time to.

The uniform flow equation can be written (Smith and Woolhizer 1971) as :

$$q = \alpha h^{D} \quad . . . . . . (3.15)$$

Equations (3.12) ,(3.14) and (3.15) can be used to compute the entire outflow for a single plane segment from a constant lateral outflow rate of Rx (Rovey et al 1977).

3.6 TYPES OF RUNOFF

Overland flow is that part of surface runoff which flows in a thin sheet flow over the land surface down the slope. Many researchers have analysed and reviewed types of overland flow: laminar, turbulent, or transitional flow, most agreeing that all three forms are encountered. Generally, flow changes from laminar to turbulent, and back to laminar through the rise and recession of the hydrograph. These regimes are often distinguished from one another by discontinuities in curves, which show the relationship between the discharge and time on logarithmic paper.

Whether, flow is laminar or turbulent, is not clear and there is disagreement in the literature. There are also no clear guidelines of how and how much of the rainfall impact affects the roughness. For the effect of this on flow type Yoon and Wenzel (1971) showed that the raindrop impact increases the roughness and results in the flow being turbulent, at lower intensity. Chen (1976) ignored the raindrop impact for shallow flow over turf as long as the flow was laminar. Morgali (1970) reported that the all flows start as laminar and at higher flows, there is a change of flow regime, which may be approximated by a turbulent-manning slope. Kilinc and Richardson (1973) reported that the flow can not be strictly called laminar, but neither is turbulent. Engman (1986) stated that the assumption that all runoff flow is turbulent appears to be justifiable for engineering applications.

The determination of the roughness coefficient for laminar and turbulent flow is different. In this study the runoff flow will be assumed to be turbulent flow and that Manning's n is constant. The constant in equation (3.14) can be expressed as :

$$\alpha = S^{0.5}/n , \quad D = 1.67 \quad . \quad . \quad . \quad . \quad . \quad (3.16)$$

where:

n = manning's roughness cofficient

The determination of roughness coefficient for turbulent flow is based on the selection of n values determined for channels, streams, and canals. These values of n can be found from various sources, such as Chow (1959), Morgan (1980), and

Hudson (1981). For the flow on a plane surface the D values can be fixed in both the laminar and turbulent flow, with only the parameter of roughness being varied (Wu et al 1978).

3.7 CONCLUSION

Rainfall-runoff models are used for prediction and simulation of surface runoff and are important in the design and operation of water resource systems. The rainfall-runoff process is essentially non-linear due to the non-linear relationship between many of the components of the process such as soil moisture and evapotranspiration (Patry and Marino 1983). This review has provided a summary of the kinematic wave models and the development of this theory as an appropriate means of computing some categories of gradually varied unsteady flow. It is clear that there are many ways in which the processes can be described mathematically. The aim of studying runoff is to find a technique for predicting the behaviour of a catchment during rain. A mathematical simulation model will be a good method of approach. This simulation model could be used to predict for example runoff at the bottom end of a strip of sloping land. Such a model would be a valuable tool for the design and management of low pressure irrigation systems.

The kinematic wave equations have been used to simulate runoff and considerable quantity of work has been done on the mathematics of simulation models. Complex and relatively small catchments have been considered by many investigators.

In this study it is proposed to use the kinematic wave equations as a mathematical model for predicting surface runoff from a simple catchment. The model developed in this study is designed to predict runoff from a very small catchment of the order of 0.5 m in length with variable slopes as occur in ridge and furrow cultivations; a common cultivation practice used for growing irrigated crops. Previous studies have invariably related to large scale catchments, but it is anticipated that model can be developed which will be of value to irrigation system designers and to farmers.

Considering the model requirements which include variable application rates, infiltration rate, and soil slopes, an implicit finite difference model using the continuity equation and the simplified momentum equation appears most suitable for the purpose of this study. The finite difference solution to be used is Brakensieke's four point implicit finite difference scheme (Brakensiek 1967). The kinematic wave solution will be then coupled with the modified Kostiakov's infiltration equation to predict the surface runoff.

CHAPTER 4

RUNOFF MODEL DEVELOPMENT

4.1 INTRODUCTION

This chapter describes the development of a surface runoff model based on the kinematic wave theory (called sroff) capable of calculating surface runoff under different water application rates and different soil infiltration rates with different catchment slope conditions as occur in ridge and furrow cultivations. To program the model for the computer, a finite difference approach is used.

4.2 EQUATIONS DEVELOPMENT

The movement of surface runoff is described by the equations of continuity, momentum, and the modified-Kostiakov infiltration.

a) continuity equation :

$$dq/dx + dh/dt = RX \quad . \quad . \quad . \quad . \quad . \quad (4.1)$$

b) momentum equation :

$$q = \propto h^{D} \quad . \quad . \quad . \quad . \quad . \quad (4.2)$$

c) modified-Kostiakov's infiltration equation :

$$I = k\ t^{-n1} + C \quad . \quad . \quad . \quad . \quad . \quad (4.3)$$

d) The fourth equation for the lateral outflow (Rx), which is application rate (R) minus infiltration rate (I):

Rx = R - I . . . . . (4.4)

4.3 NUMERICAL SOLUTION

Equation (4.1), the continuity equation is converted to a finite difference equation as the first step for numerical solution. The numerical analysis must consider the order of approximation and the stability for the finite difference scheme. The former ensures that the finite difference equation is solving the differential equation, and the latter ensures that the computational errors or roundings do not destroy the solution by error growth, Brakensiek (1967).

The terms of equation (4.1) are approximated with the implicit finite equations based on a rectangular point array (Brakensiek, 1967) as shown in figure (4.1) and the equations below.

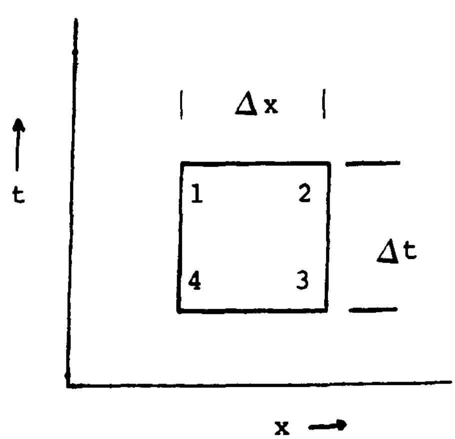


Figure 4.1 rectangular grid used to set up finite difference equations.

Using the approach of Brakensiek (1967), the partial differentials were approximated by :

$dq/dx = q2-q1/ \Delta x$ . . . . . (4.5)

$$dh/dt = (h1+h2-h3-h4)/2\ \Delta t \quad . . . . . \quad (4.6)$$

Combining equations (4.5) and (4.6) gives :

$$q2-q1/\ \Delta x + (h1+h2-h3-h4)/\ 2\ \Delta t = R - I \quad . . . . \quad (4.7)$$

re-arranging the equation gives :

$$2\ \Delta tq2 + \Delta xh2 = 2\ \Delta t\ \Delta x(R-I) + \Delta x(h1+h3+h4)+2\ \Delta tq1 \quad . . \quad (4.8)$$

The solution for the finite difference scheme proceeds from the upstream boundary of the plane, and the depth of flow a long the plane is to be computed. The initial and boundary conditions may be assumed to be :

$$h(x,0) = 0$$

$$h(0,t) = 0$$

Applying the boundary conditions AT THE X-T PLANE. The unknown quantities at first grid will be at point 2,and the other quantities are known, so equation (4.8) can be reduced to :

$$2\ \Delta tq2 + \Delta xh2 = \Delta t\ \Delta x(R - I) \quad . . . . . \quad (4.9)$$

re-arranging the equation to :

$$2\ \Delta tq2 + \Delta xh2 - \Delta t\ \Delta x(R - I) = 0 \quad . . . . . \quad (4.10)$$

To solve the equations, (4.2) can be substituted into equation (4.10) to give an equation of one unknown variable as follows:

$$\Delta t\ \alpha h2^{D} + \Delta xh2 - 2\ \Delta x\ \ \Delta t(R-I) = 0 = F \quad . . . . . \quad (4.11)$$

or, to simplify computation equation (4.11) can be written as:

$$A\ h2^{D} + B1\ h2 - P = 0 = F \quad . . . . . \quad (4.12)$$

where :

$$A = 2\alpha\Delta t$$
$$B1 = \Delta x$$
$$Rx = R - I$$

$$p = 2 \Delta x \Delta t Rx$$

The computation of the surface runoff depth (h), and the runoff rate at any grid can be determined in x or t directions. The flow rate is determined from equation (4.2), and assuming the flow regime is turbulent, and manning equation is used the discharge per unit width will be :

$$q = 1/n \; S^{0.5} \; h^{D} \quad . \; . \; . \; . \; . \quad (4.13)$$

in which:

$$\alpha = S^{0.5}/n, \text{ and } \; D = 1.67$$

Equation (4.12) was programmed for the computer, and the zero roots of the equation were found by using the Newton-Raphson method. The method is simply a repetitive iteration of equation (4.12). The iterative procedure continues until F is sufficiently close to zero to give accuracy to the desired significant figures.

$$h2)i = h2)i\text{-}1 - F/F' \quad . \; . \; . \; . \; . \quad (4.14)$$

where :

F' = first derivative of F

$$F' = D \, A1 \, h^{D-1} + B1 \quad . \; . \; . \; . \; . \quad (4.15)$$

It was assumed that during the development of the model that depression storage is negligible on the flow plane, so surface runoff would begin when the irrigation application rate exceeds the infiltration rate.

4.4 STABILITY AND CONVERGENCE OF SOLUTION

The efficiency of the implicit finite difference method is determined on the basis of convergence of the numerical solution and its stability. Thus the values of Δx and Δt must be chosen. It was hoped that they could be chosen independently without problem of stability and convergence.

A stability analysis to choose Δx and Δt was made and, that covered a wide range of Δx and Δt values. A stability and convergence analysis was also made. A series of runs were made to to investigate the stability using different values of Δx and Δt. In a series of runs Δx was kept constant varying only Δt, all other parameters kept constant. Time increments tried were 0.1, 0.2, 0.24, 0.5, 0.7, 0.9, 0.95, 1.0, 2.0, 3.0, 4.0, 6.0, 8.0 and 10 seconds and each run was allowed to reach 90 minutes. The distance increments of 0.1, 0.2, 0.3, 0.4, and 0.5 m were varied with the various time increments. The values of Δx = 0.5 m and Δt = 8 seconds for low application intensity, and Δx =0.5 m, and Δt = 4 seconds for high intensity were gave good results and were chosen as the value to be used in the study for soil A (see section 5.5.1). The plane length in the experiment (see section 5.5) was very short and that limited the investigation of the method for Δx above 0.5 m.

For soil C (see section 5.5.1) another stability and convergence analysis was made because the soil infiltration rate has changed , therefore another investigation for the stability of the numerical solution when the the infiltration was changed in the model is required. A series of runs were made using different values of Δx, and Δt. It was found that the values of Δx = 0.5m, and Δt = 0.95, and 0.24 second for low intensity and high intensity applications, respectively gave a good results and were chosen for soil C. The simulation results showed that this type of numerical solution is more sensitive to the time increment.

4.5 MODEL OPERATION

To numerically evaluate the surface runoff model (sroff), a computer program was written in Fortran-77 for use on VAX/VMS version V4.6 computer. A flow chart showing the various steps of the computational logic utilized in the model is shown in figure 4.2. SROFF computer program can be seen in appendix A.2, and typical model output in appendix A.2 (table 1).

The program operates by reading data (input data) and screen management routine, then calculates infiltration rate and lateral outflow. The program will determine when the runoff begins. Then the finite difference solution is used to determine the initial depth of runoff over the catchment for the chosen time increment. The runoff discharge will be calculated at each time increment at the bottom end of the catchment. The runoff calculated at the end bottom of the catchment depends on the application rate, catchment slope, and soil infiltration rate. This computation process is repeated when the input is changed. The required time to run the program is dependent on the selected time increment and the maximum simulation time required.

Features that can easily be included in the program are a variable infiltration rate, a variable irrigation application rate, and a variable catchment slope. The model represented by this program can determine the surface runoff on short slopes of 0.5 m for chosen time increment, and the amount of water infiltrated into the soil.

The program includes Newton-Raphson method to find the zero roots of the equations. Shown below are the programming input

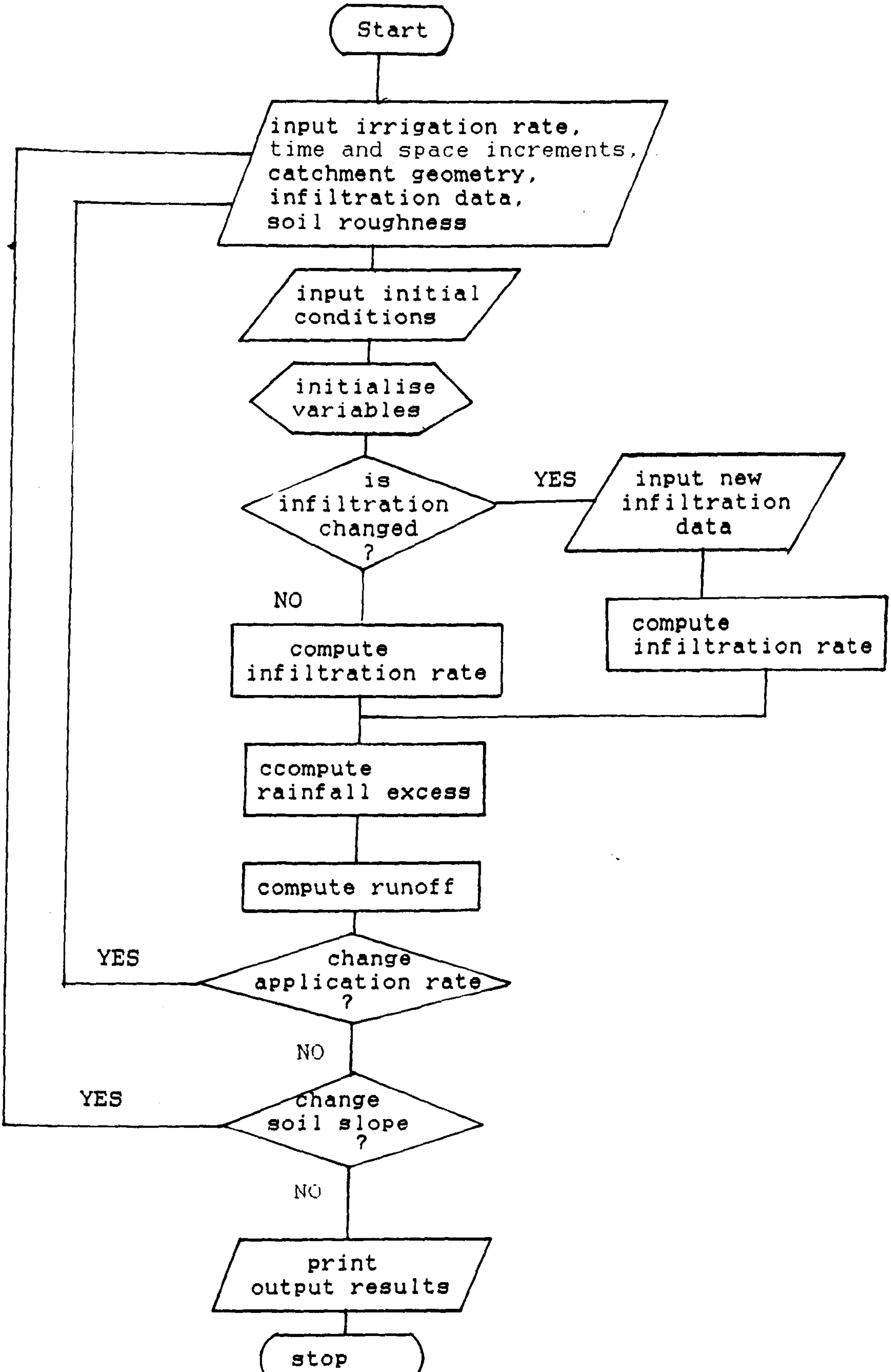


Figure 4.2 Flow chart of program SROFF.

data and output data.

4.6 INPUT AND OUTPUT DATA

Input data

Input data are utilized by the computer model to sequentially compute the surface runoff from each segment. The computation begins on the segment at the highest elevation of the plane and continues down slope to the lowest point on the plane.

DX - distance increment (m)

DT1,DT2 - time increment (sec.)

RAIN1,RAIN2 - irrigation application rate (mm/hr)

D - exponent for overland flow that is related to flow regime

n - Manning roughness coefficient

S slope plot (%)

k, nl, C - constant for infiltration equation $i = kt^{-nl} + c$

L - Plane length (m)

W - Plane width (m)

Output data

FIL - infiltration rate (mm/hr)

H(I,J) - surface runoff depth (mm)

Q(I,J) - runoff discharge (m2/sec)

TX(I) - time of irrigation (hr)

RUN(I) - surface runoff rate (mm/hr)

RNO(I) - surface runoff (mm)

4.7 CONCLUSION

A surface runoff model (SROFF) has been developed using the continuity equation, and the simplified momentum equation.the model equations were chosen, developed, and combined with interacting boundary conditions at the soil surface to provide a mathematical model for the generation of surface runoff from irrigation on an infiltrating surface. The solution method used is Brakensiek's four-point implicit finite difference scheme,and it was chosen for its computational stability and ease of implementation. The numerical solution will be tested statistically to judge the agreement between measured and predicted results of the surface runoff.

CHAPTER 5
RUNOFF MODEL VALIDATION

5.1 INTRODUCTION

To validate the runoff model experiments were designed and carried out in the laboratory on a bare soil over a wide range of conditions to obtain data that could be compared with that predicted by the model. A range of irrigation application rates with two different soil slopes, and two soil conditions were chosen,so that significant differences could be expected in both experimental and simulated data for comparison.

5.2 EQUIPMENT

A stationary spray system was constructed for this study which consisted of an electric pump, pipe line, pressure gauge, and spray nozzles (figure 5.1). The spray nozzles were fixed to a flexible hose at regular spacings, and attached to a boom. The boom was supported by two movable stands. The two stands have a number of holes drilled into them at regular intervals to adjust the height of the nozzles from the soil surface by raising or lowering the spray boom.

Water is pumped to the spray nozzles through pipes, and a valve is used to control discharge. A standard pressure gauge, which indicated the pressure in kpa, and ıb/in2 was used. This pressure gauge was installed at the end of the flexible hose at 200 mm from the last nozzle, the operating pressure was fixed at

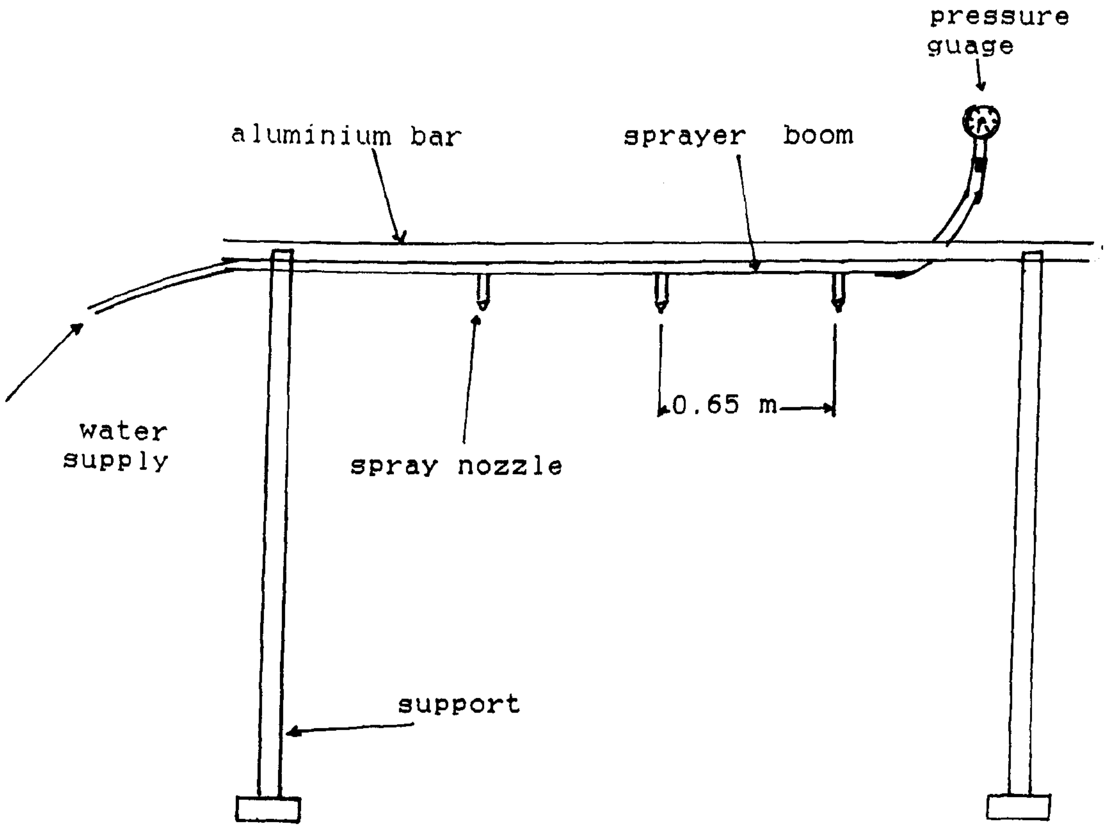


Figure 5.1 Schematic diagram of the sprinkler application system.

103 kpa (15 ib/in2) through out the experiment.

Three spray nozzles of different sizes were selected for the experiment (table 5.1). The selection of the nozzle types and sizes was based on the requirement for a high application rate and a high level of jet breakup to distribute the water uniformly over the irrigated area. The nozzles chosen were the full cone fixed spray nozzles, with a spray angle of 120 degrees, with different diameters. This type of nozzle is currently used on low pressure sprinkler systems.

Nozzle (code no.)	orifice diam. nom.(inch)	capacity at 103 kpa (l/s)	wetted diam. (m)
1/8GG 2.8W	1/16	0.0226	2.26
1/8GG 8W	3/32	0.0618	2.38
1/4GG 14.W	1/4	0.1098	2.48

Table 5.1 fulljet spray nozzles specification.

One of the main criteria in selecting suitable nozzle types for use at low pressure is the degree of jet breakup. The drop size distribution for the three spray nozzles was determined for each nozzle type by Deacon (1981) using the stain method. The nozzle under test was mounted at a height of 0.5 m above the ground and pointing vertically downwards. The drop size distributions for the fulljet spray nozzles at pressure of 80 kpa are shown in figure 5.2. From the figure it can be seen that the nozzles produce relatively small drops but the drop diameter is increased with the increase of nozzle diameter. A common measure of the size of droplet produced from nozzles from which comparisons between different nozzles may be made is the D50

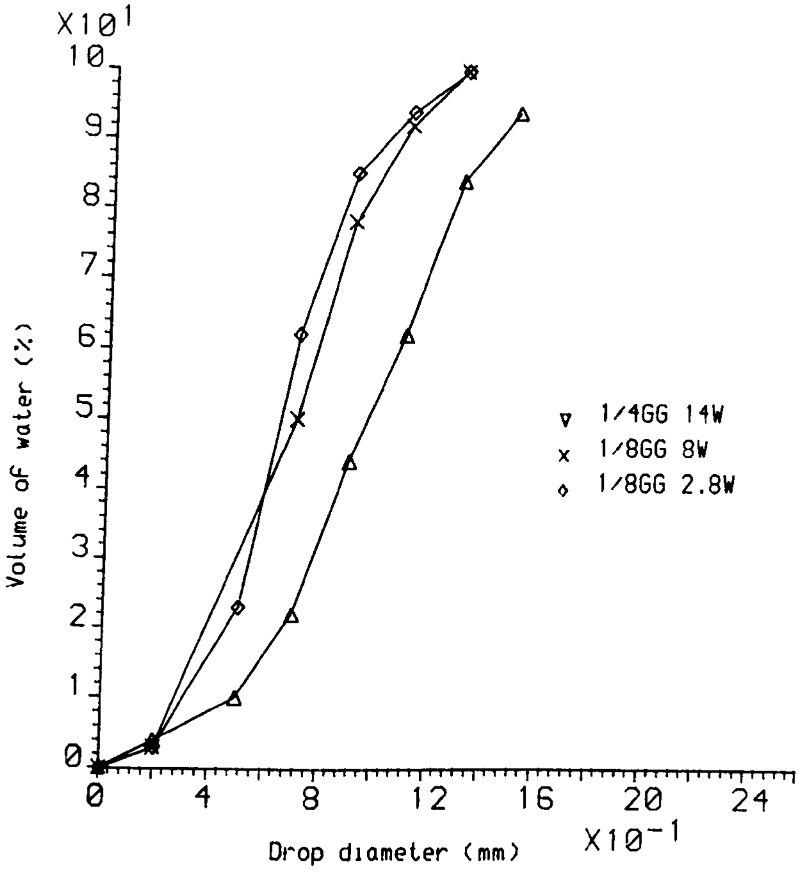


Figure 5.2 Cumulative drop size distribution from spraying system fulljet nozzles at operating pressure of 80 Kpa (after Deacon 1981).

value. This is the drop size corresponding to the 50% cumulative volume of water. The D50 values obtained from the curves in figure 5.2 are 0.65, 0.70, and 0.97 for 1/8GG 2.8W, 1/8GG 8W, and 1/4GG 14W nozzles, respectively.

5.3 APPLICATION RATE

Three application rates were chosen in the study. These were 100, 300, and 482 mm/hr. The selection of these application rates was made according to the observations of other investigators involved with the development of low pressure system (see section 2.3).

The application rate and uniformity over the irrigated area was measured by setting catch cans on a regularly space pattern over the irrigated area, measuring the depth of water caught and the time of application at each can for each application.

Each test was run at an operating pressure of 103 Kpa (15 ib/in2), and each test was repeated three times. preliminary tests were conducted with each type of nozzle, to select a suitable height of the nozzles from the soil surface, and the spacing between the nozzles on the boom to give the required application rates.

5.4 UNIFORMITY OF WATER APPLICATION

The nozzle height above soil surface ranged from 0.95 m to 1.3 m, and the spacing of 0.65 m between the nozzles on the sprayer boom.

The spray patterns were obtained by catching water from a single nozzle (figure 5.3), and each type of nozzle shows that

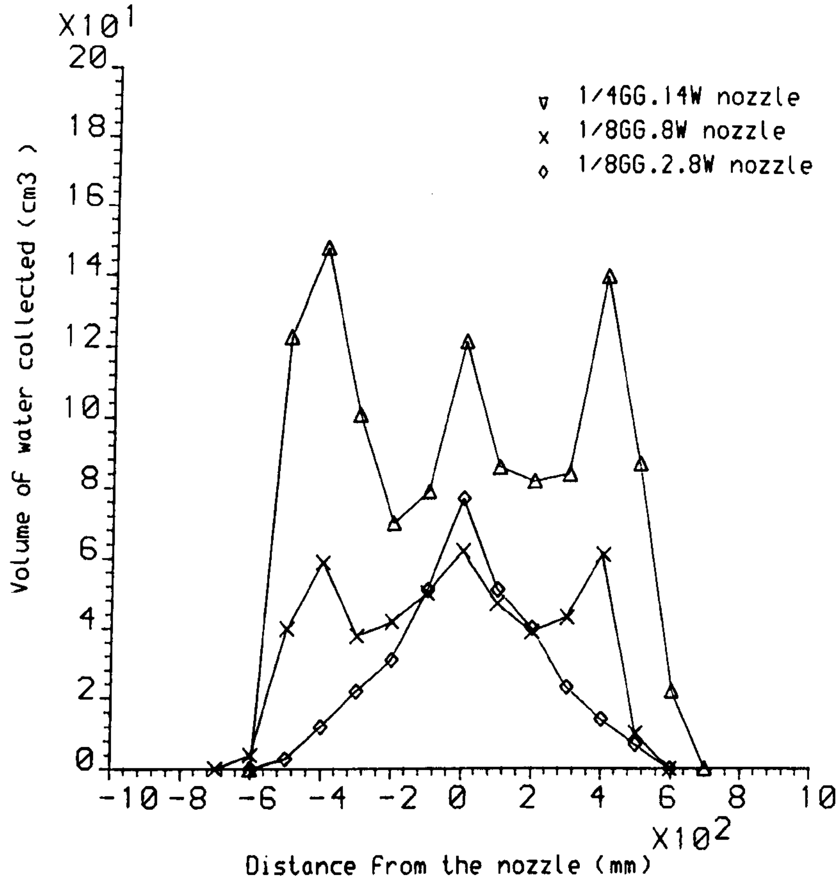


Figure 5.3 Water distribution patterns for three fulljet spray nozzles at operating pressure of 103 Kpa.

the peak application rate occurs some distance from the nozzle, thus producing a dough-nut shaped distribution around the nozzle. The rate of water application for each set of nozzle sizes was calculated by dividing the depth of water caught by the time of water application.

The water distribution patterns from a single nozzle were used to determine the overlap required to distribute the water uniformly over the irrigated area. The uniformity of water application was determined using the Christiansen's coefficient of uniformity (Cu) (Christiansen 1942) defined as :

$$Cu = 100 \left(1- \sum x / MN \right) \quad . \quad . \quad . \quad . \quad . \quad (5.1)$$

x = is the absolute deviation from the mean of individual observations.
M = is the mean value of observations.
N = is the number of observations.

The application rates, and Cu values for each nozzle size are listed in table 5.2

nozzle type code no.	no.of nozzle	nozzle height (m)	nozzle spacing (m)	Cu over soil box (%)	Cu over wetted area (%)	appli. rate (mm/hr)
1/4 GG.14W	2	0.95	0.65	91	74	482
1/8 GG.8W	3	1.10	0.65	86	55	300
1/8 GG.2.8W	1	1.30	0.65	66	62	100

Table 5.2 Application rates and cu values for test nozzles.

There are two values of uniformitY for each nozzle size; first over the soil box area, and second over the whole wetted area to give an idea of the uniformity for comparison. The values of Cu which are concerned with the experiment over the soil box area lie between 66-91%. The pattern of water distribution within the wetted pattern under low pressure was dough-nut shaped and this affected the uniformity of water application. The high application rates (300, 482 mm/hr) produced a dough-nut shaped pattern, but low application rate produced a triangular pattern. The uniformity of application as indicated by the Christiansen coefficient of uniformity, over the soil box for application rates 300 and 482 mm/hr exceeded the acceptable uniformity level of 80%, but the low value of 100 mm/hr application rate was below that level. This was probably due to using only one spray nozzle because one nozzle was enough to obtain the required 100 mm/hr average application rate over the soil box area. It was found that the water application uniformity increased with increase in nozzle diameter and the application rate.

5.5 SOIL

The soil used in this experiment was collected from the college farm at flitton, the same site used for the field evaluation (chapter 8). The soil was collected from a depth of 0-400 mm from the soil surface. A soil mechanical analysis was carried out using the Pipette method to determine the relative proportions of the different sized soil particles. Different soil samples were taken from different locations at different depths at random from the field site and the results obtained are shown in table 5.3.

Depth (mm)	sand content (%)	silt content (%)	clay content (%)	soil type
100	28.71	27.86	43.43	clay
200	28.83	26.53	44.64	clay
300	23.03	28.26	48.71	clay
400	28.08	25.73	46.19	clay

Table 5.3 soil mechanical analysis and soil type.

The soil was air dried, and then sieved through a 12.5 mm mesh sieve. The average soil water content was about 8% by weight.

To expose the soil to irrigation, soil boxes were designed with dimensions of 1.0 m long, 0.5 m width, and 0.06 m deep. Many small holes were drilled into the bottom of each box to allow infiltrated water to drain freely. Then the soil boxes were placed under the simulator, at two different slopes, namely 10%, and 30%, respectively one at a time. A special layer of cloth covered the bottom of each box, to act as a filter and to prevent any blockage of the small holes. Slope steepness is an important factor in runoff potential especially with steep slope such as that of ridge sideslope. Therefore, slopes of 10 and 30% were chosen (see sections 2.5, 2.7), this will help to make comparison, and to predict the amount of runoff.

Soil was then placed in each of the boxes and uniformly compacted by metal roller until they were full. The bulk density average was 1.1 gm/cm3.

5.5.1 Soil Infiltration

The effects of soil structural breakdown from the various application rates and method of application was assessed by measuring the soil infiltration rate for the soil before and after an irrigation. This provided an ideal measure from which comparisons from before and after irrigation could be made. Also the infiltration rate of the soil was measured because this is one of the main inputs into the mathematical model. Measurements were made on three different soil conditions. The first soil sample had not been exposed to irrigation, however the second sample had been exposed to two irrigations at 482 mm/hr, and third soil sample was exposed several times to a similar intensity of irrigation.

A plastic cylinder of 100 mm in diameter, and 500 mm long was used. The soil was air dried and sieved, and uniformly compacted in the cylinder to a depth of 60 mm, similar to the soil depth in the runoff measurement tests.

A measured quantity of water was added to the cylinder to give a depth of 50 mm above the soil surface, which was marked on the cylinder. The water level above the soil surface was not allowed to fall below 20 mm each time this point was reached water was added. The readings were taken for the elapsed time, and the volume of water added. Each test was repeated three times. A fresh soil sample was used each time.

The results of measured infiltration rate by the cylinder infiltrometer are shown in figure 5.4. These infiltration rates are for one type of soil. The soil was divided to three samples

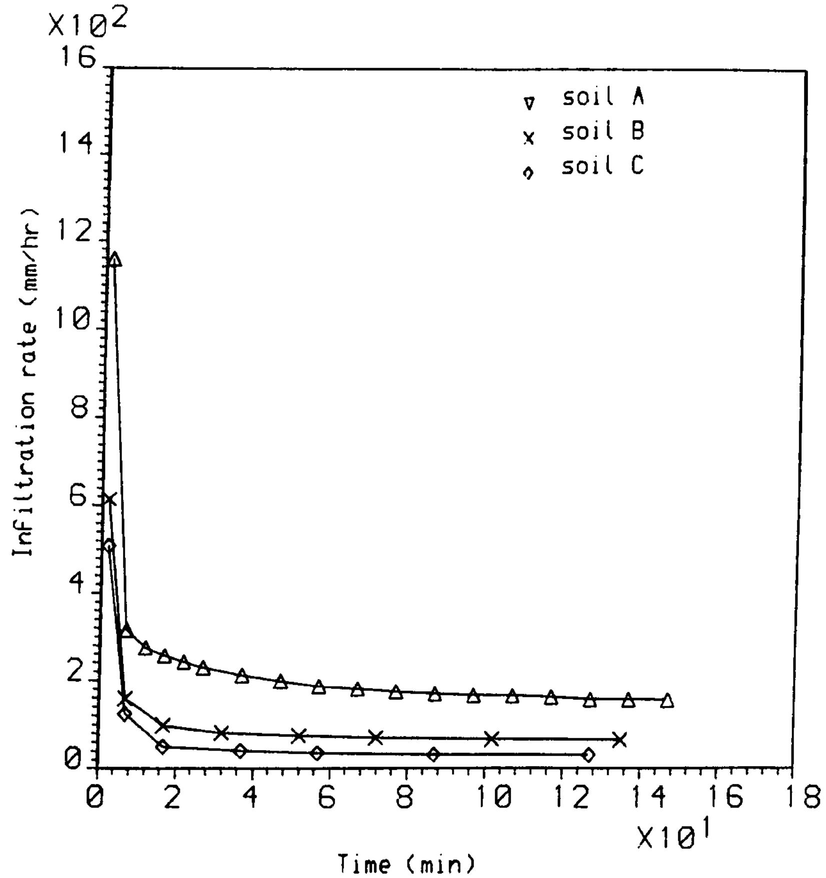


Figure 5.4 Infiltration rates for three different soil conditions.

according to their particle sizes as follows:

soil A - not exposed to irrigation.

soil B - exposed to two irrigations.

soil C - exposed to the several irrigations.

It was decided to use soil infiltration data of soils A and C in the model inputs, because it was noticed during the experiments that runoff increases with one soil sample if the same soil used more than once. Because the infiltration for each soil sample is changing each run, and the assumption of one infiltration rate for all samples would be highly questionable. Therefore, soil A and soil C have been chosen because they have the highest and the lowest infiltration rates. And it was then decided to use this change of soil infiltration data in the model development. The soil particle size distribution for soil A and soil C are shown in figure 5.5. The initial soil water content for each experiment was about 8 % by weight.

Numerous studies have been conducted on the problem of infiltration changes due to raindrop energy impact, and soil surface sealing. such as Ellison (1947), Mcintyre (1958) , Epstein and Grant (1967), Morin and Cluff (1980), and Mohammed and Kohl (1987). It can be seen in figure 5.4 that the infiltration rate was high for soil A because of the greater space between the soil particles. Infiltration rates for soil B and C were less than soil A, because with exposure to irrigation, soil breakdown and surface sealing occurred. Moldenhauer and Kemper (1969) showed that the impact forces of raindrops falling on soil fragments can destroy the normal soil structure almost completely and leave mainly dispersed silt particles, or silt-size clay aggregates on the surface.

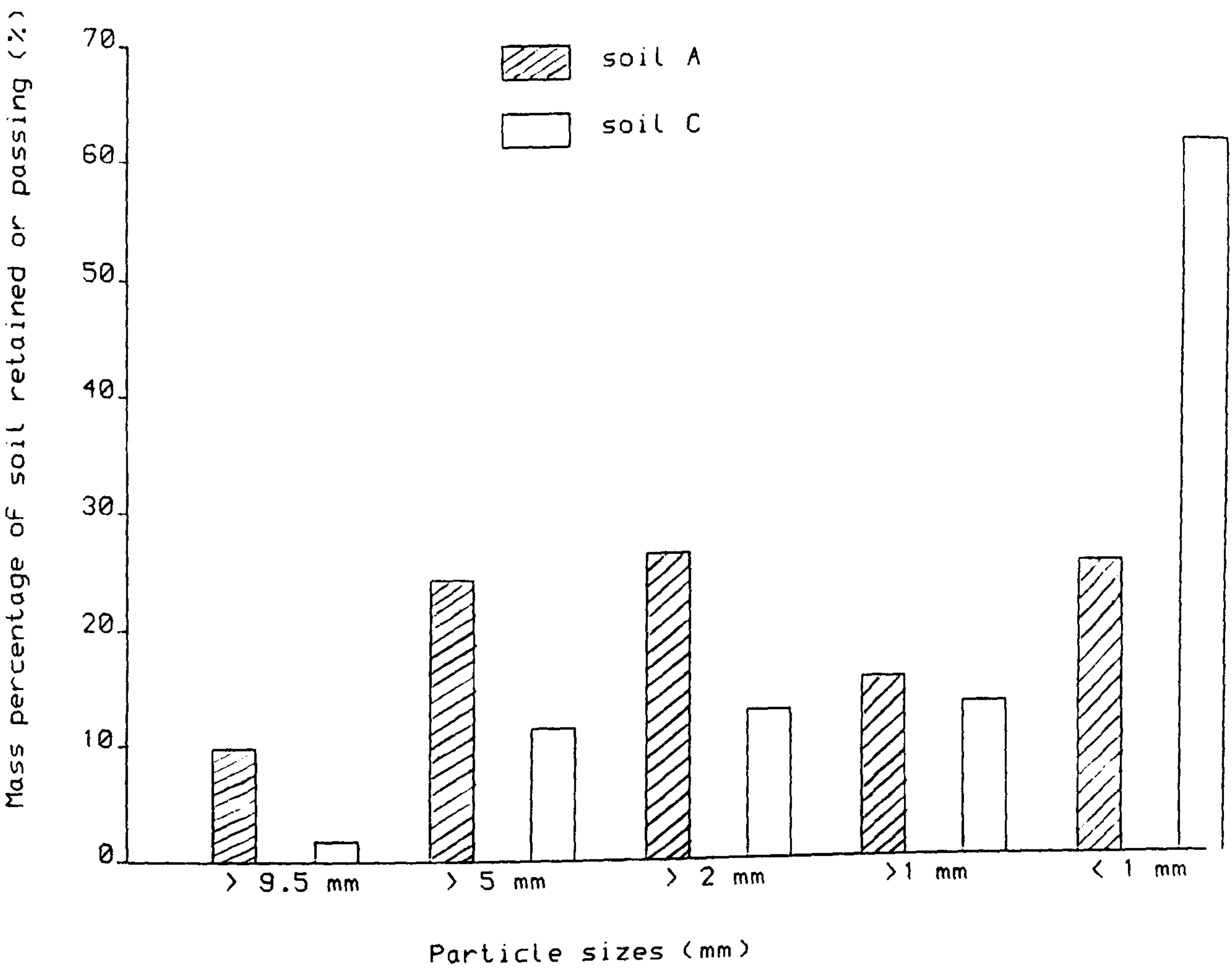


Figure 5.5 Particle size distribution for two soils

The method of least squares was used to determine the infiltration constants for the three curves based on the simplified Kostiakov equation. The constants k and nl were determined to give the infiltration rate in mm/hr as a function of time in hours. The values of the constants are listed in table 5.4. These particular values of k and nl represent a fairly wide range of soil conditions.

soil	nl	k
A	-0.25	185
B	-0.34	74
C	-0.40	36

Table 5.4 Values of infiltration constant parameters.

To determine whether the infiltration rate of the three soils differ from each other significantly, a test of homogeneity of regression coefficient on the three curves was carried out. It was found that the infiltration rate curves differed significantly at 5 % level, but not at 1 % level.

An infiltration equation to be linked with the surface runoff model is needed to predict the time at which surface saturation or ponding occurs, and to describe the infiltration thereafter. The equation used in the model is the modified-Kostiakov equation. The reason for choosing this equation is discussed section 2.6. The equation can be written as follows :

$$I = k\, t^{-nl} + C \quad . \quad . \quad . \quad . \quad . \quad (5.2)$$

c is constant, and is added from the beginning of the infiltration rate. This is because the Kostiakov's equation was developed under the assumption, that infiltration rate is independent of the application rate during the initial period of application rate. As time increases, the infiltration rate gradually decreases towards zero, and the equation becomes very unreliable. So, the constant c was added to modify the equation for sprinkler irrigation, and this constant is equal to the lowest final infiltration rate obtained for soil c which was 20 mm/hr after the end of the experiments.

The change in infiltration with respect to time as indicated in the infiltration tests can be used to study the surface runoff predicted by the model under different application rates at different slopes. The change in infiltration rate may reflect the true field situation of a changing infiltration rate with time.

5.6 RUNOFF MEASUREMENT

Runoff collectors were designed and attached to the soil boxes (plate 5.1) and a flexible hose was connected to each collector to carry the surface runoff to a container for measurement, as shown in figure 5.6.

The air dried soil was exposed to the different application rates 100 mm/hr., 300 mm/hr, and 482 mm/hr. The duration of sprinkler irrigation was chosen so that it would be long enough to reach steady state conditions. A general characteristic of the irrigation depth-duration relationship is the higher the intensity of irrigation, the shorter the duration of the

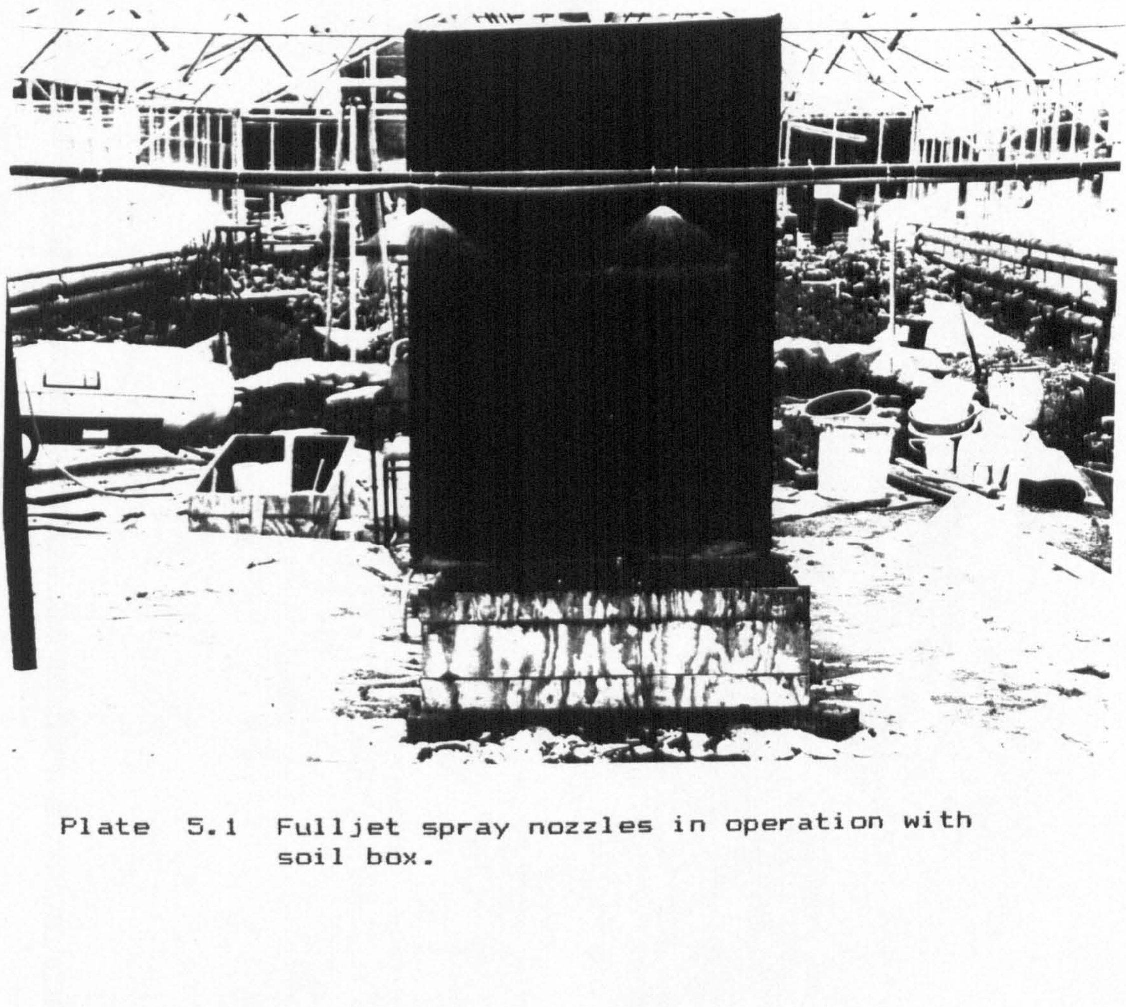


Plate 5.1 Fulljet spray nozzles in operation with soil box.

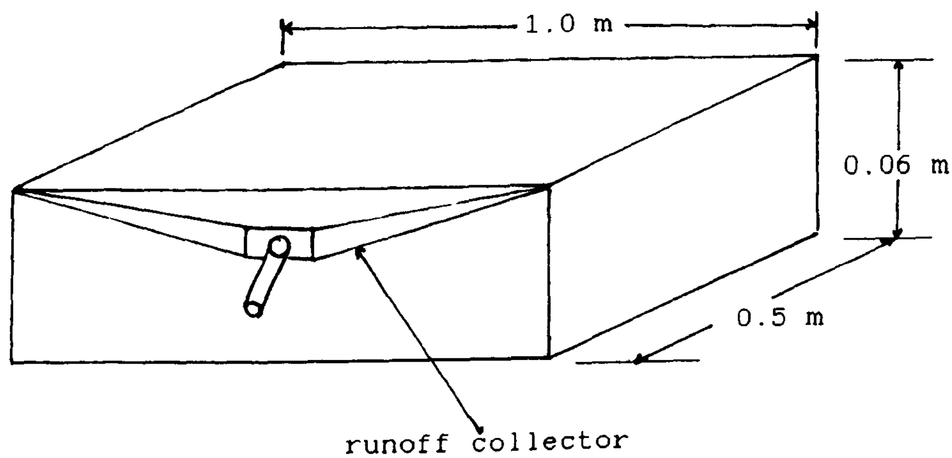


Figure 5.6 schematic diagram of soil box and runoff collector.

irrigation is likely to be.

To measure the volume of runoff caught in a container each minute, different graduated cylinders were used. Each test was run three times. The test layout can be seen in plate 5.1 showing the simulator with the soil box and runoff collection.

5.7 RUNOFF RESULTS

The results of the runoff experiments are presented and discussed in two ways:-

1) to establish that the data obtained from the experiments are reasonable. Surface runoff from different soil conditions with different soil slopes, and under different sprinkler intensities is examined.

2) to compare the data obtained from the experiments with data predicted by the model.

5.7.1 Surface Runoff

To make an interpretation of observations and measurements a comparison was made between all various sets of curves to determine the effect of each variable upon runoff. The runoff obtained under various sprinkler intensities and on two different slopes for the same soil have been grouped in figure 5.7 for soil A, and figure 5.8 for soil C. Note that there was no runoff was recorded at any time at an irrigation intensity of 100mm/hr A comparison was made between both soils at one soil slope and different application rates in figures 5.9 and 5.10.

These figures demonstrate how the runoff is related to the

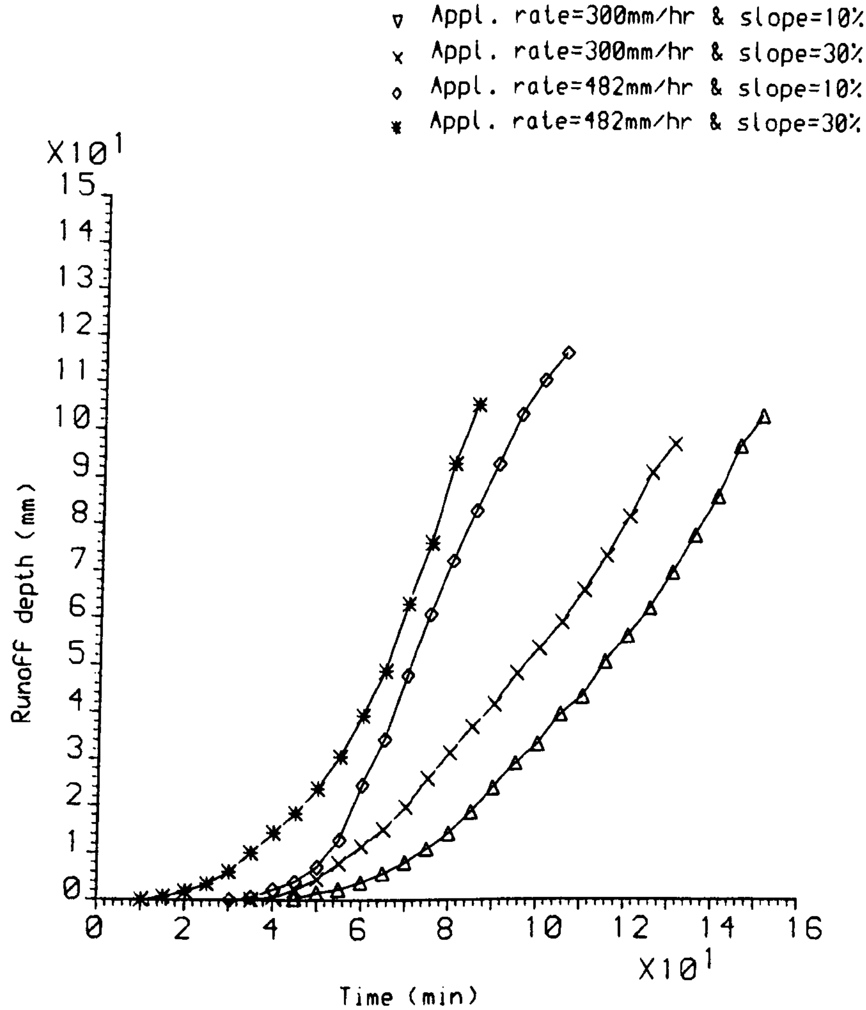


Figure 5.7 Accumulative measured runoff from soil A.

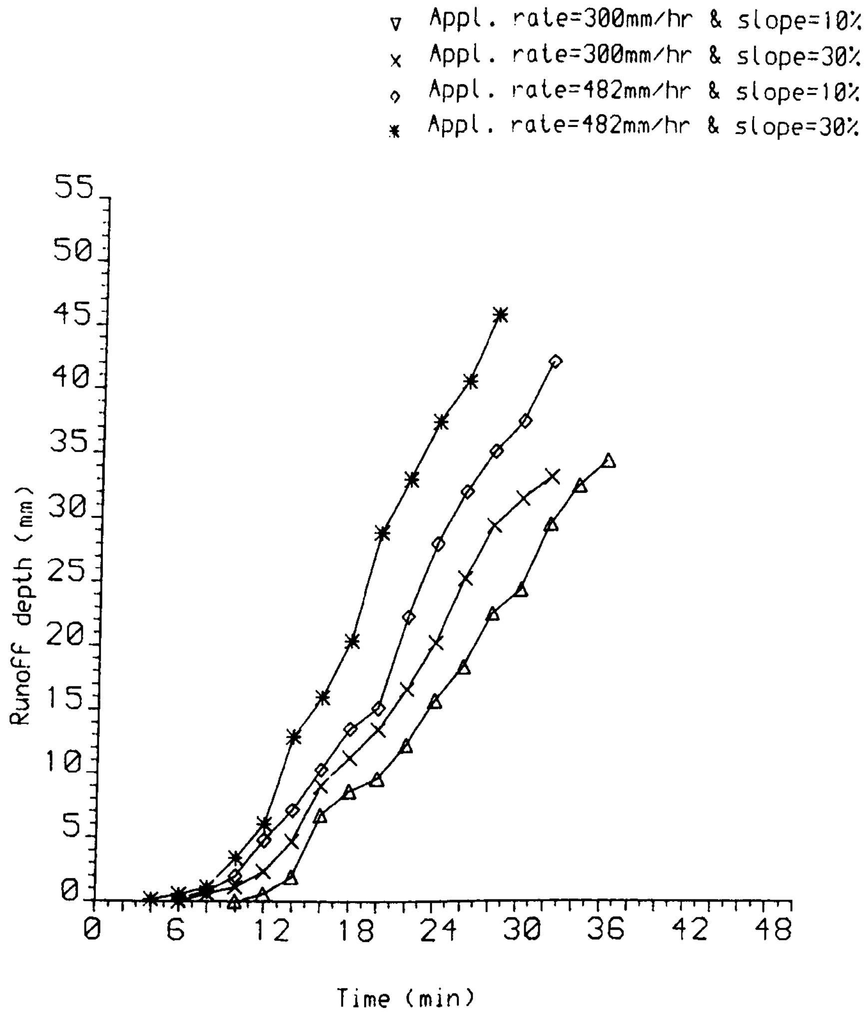


Figure 5.8 Accumulative measured runoff from soil C.

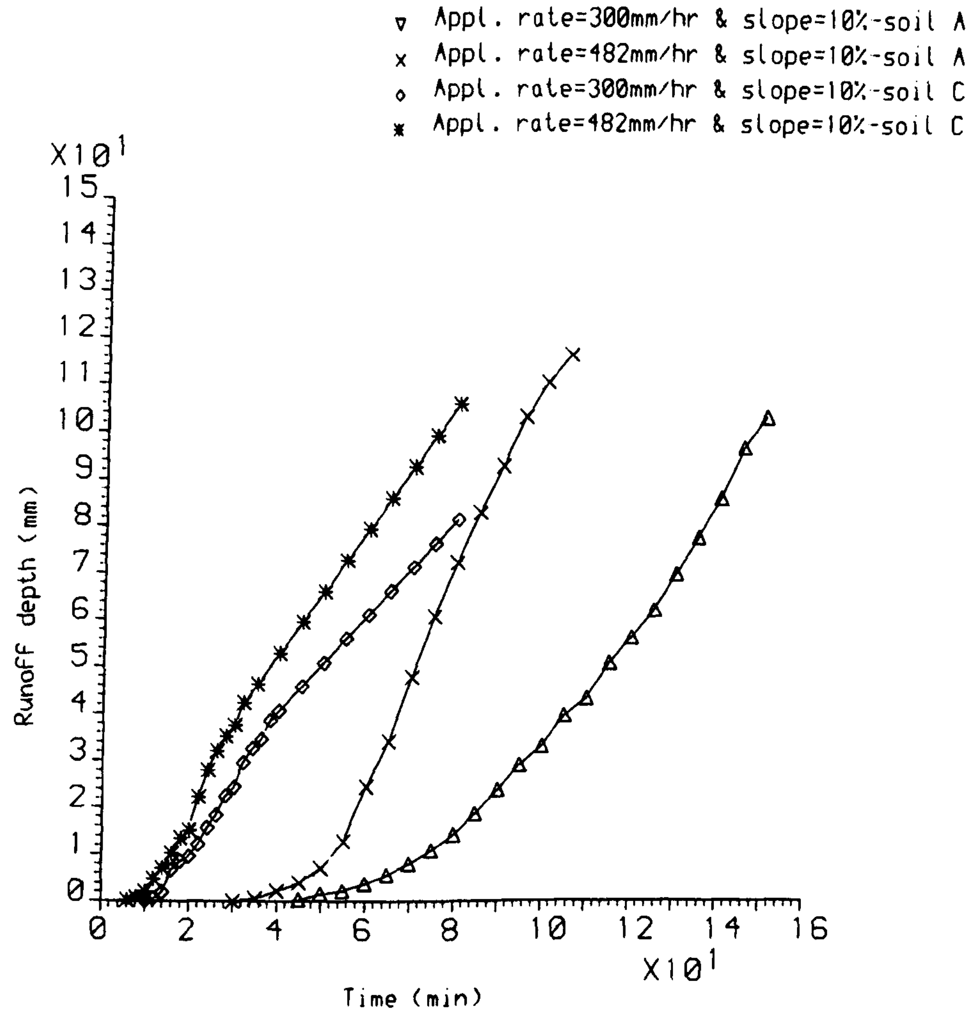


Figure 5.9 Accumulative measured runoff from soil A & C with different application rates and one slope.

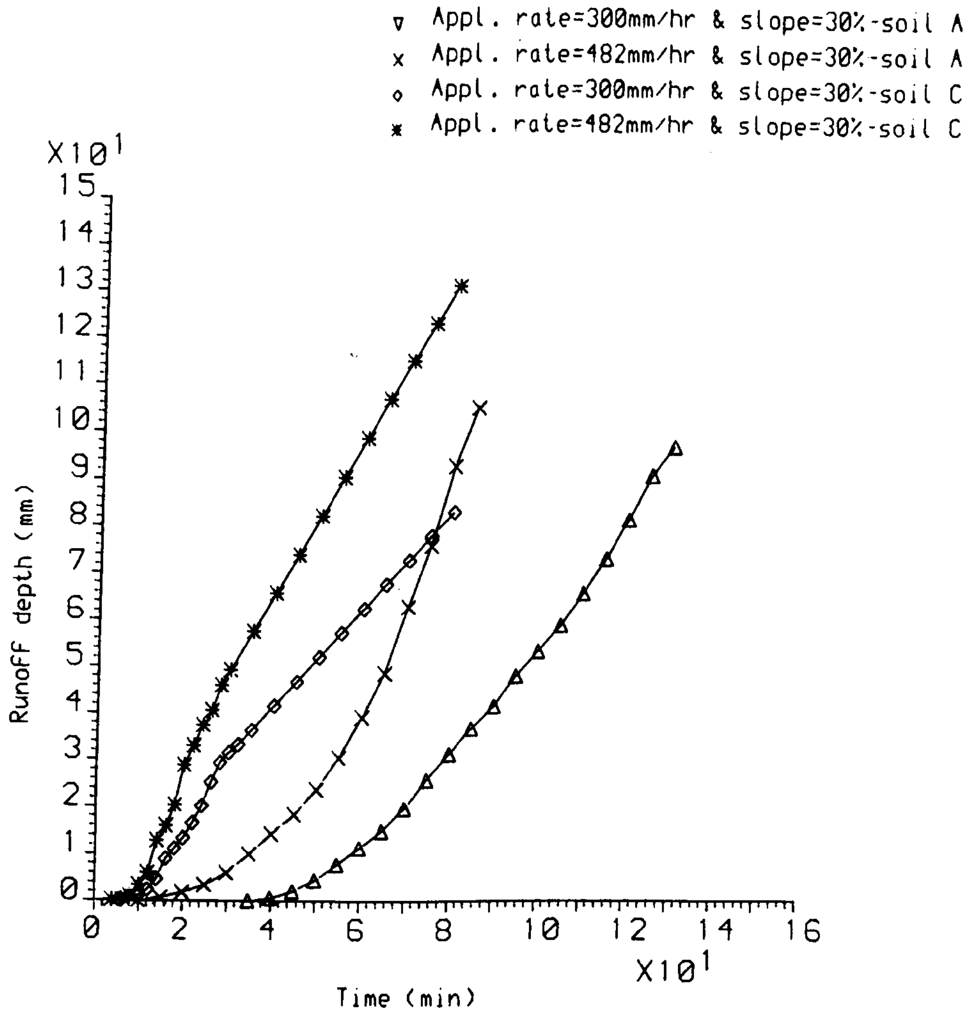


Figure 5.10 Accumulative measured runoff from soil A & C with different application rates and one slope.

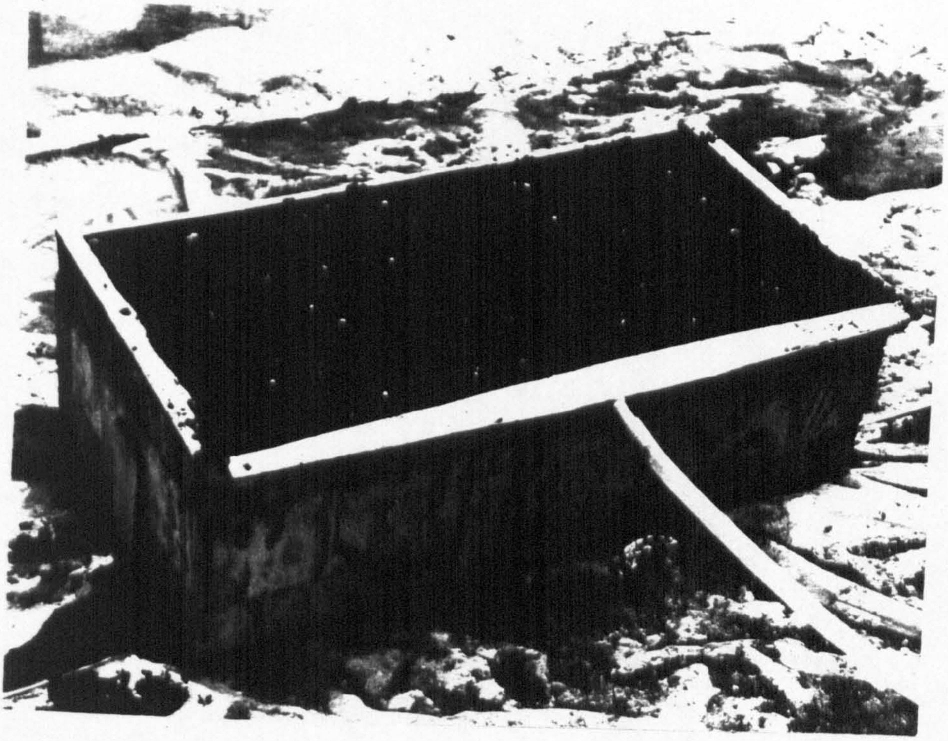
surface characteristics, rainfall intensities, and also the soil infiltration characteristics. All the graphs are based on average experimental results and the variation in runoff measurements between the replicates of each treatment was not large.

The figures show that as sprinkler intensity increases runoff starts earlier. As the slope of the catchment area is increased runoff starts earlier, and the gradient of the runoff curve increases i.e. rate of runoff increases. The steady state runoff is also reached sooner.

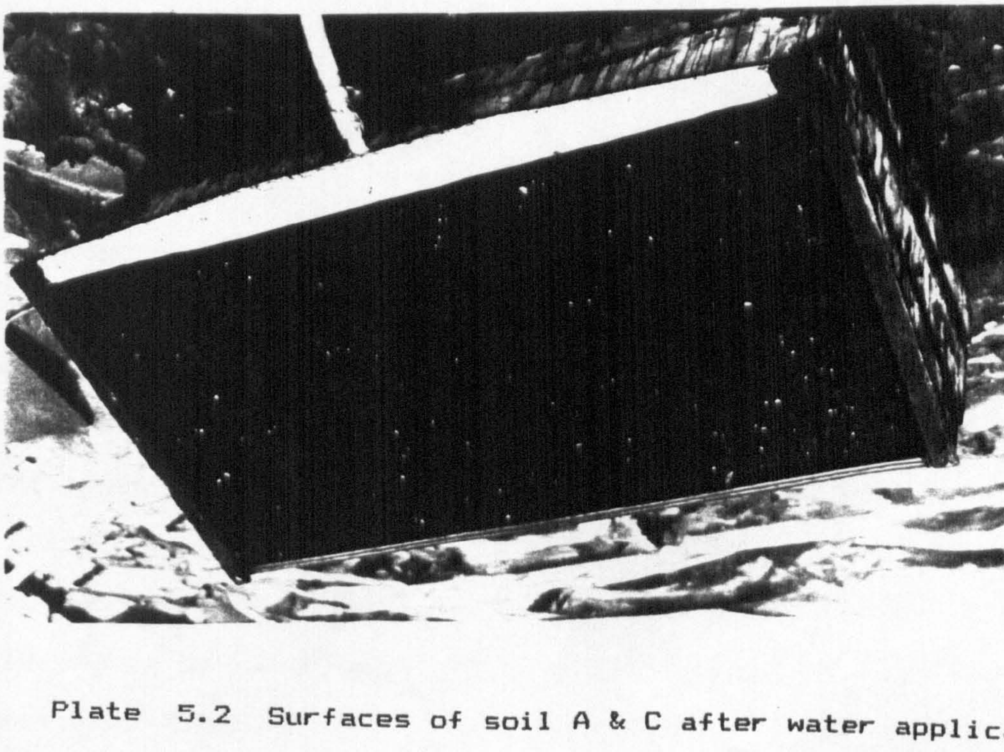
Runoff differed between soil A and soil C. Runoff was higher on soil C under similar slope and sprinkler intensity conditions and started earlier. The gradient of the runoff curves were much steeper for soil C. This is clearly a function of the reduction in soil infiltration rate for soil C. So it can be seen that the effect of infiltration rate was quite high.

The surface runoff from soil trays was a fluid composed of water with sediment in suspension. It was observed during the experiment that the sediment concentration increased by increasing the sprinkler intensity, plot slope, and decreasing soil infiltration rate. There was visual evidence of soil erosion in the form of small channels (plate 5.2) left on the surface by the running water. The extent of erosion appeared to be influenced by sprinkler intensity, plot slope, and infiltration rate.

The parameters describing the hydraulic roughness for flow under sprinkler irrigation can be evaluated from the experimental data obtained during the irrigation by plotting the measured



Soil A



Soil C

Plate 5.2 Surfaces of soil A & C after water application.

runoff rate versus time on logarithmic scales, as shown in figure 5.11 for soil A, and figure 5.12 for soil C. The change in slope of the logarithmic curves may indicate a change in flow regime and gives an indication of the flow regime (laminar or turbulent flow). From the curves it can be seen that each curve has more than one slope, and the flow started as laminar flow but after short time the laminar flow changed to turbulent flow. In general, the results show that increasing the rainfall intensity, or the slope of the plane will result in an increase in the prevalence of turbulence, and a decrease in the occurrence of laminar flow.

To determine where and when laminar flow ceases and turbulent flow exists is not easy. There is also disagreement about this in the literature (section 3.4). Considering the high application rates ranging from 100 to 482 mm/hr, the effect of raindrop impact, and the steep slope used in the experiment which tends to increase the effective roughness of the plot, the runoff flow will be assumed to be turbulent flow and that Manning's n is constant. This assumption will be used in the model to compute the runoff. This assumption of turbulent flow could be justifiable for engineering application. Since the flow is assumed to be turbulent then only the Manning coefficient (n) needs to be determined. Sufficient information exists for choosing roughness coefficient for agricultural surfaces such as Chow 1959, Woolhizer 1975, and Hudson 1981. The problem of choosing Manning's n is difficult , but one typical value of n was adopted to be used in the model. This value was 0.018 for a bare soil from Hudson 1981.

It should be noted that the kinematic wave number defined by

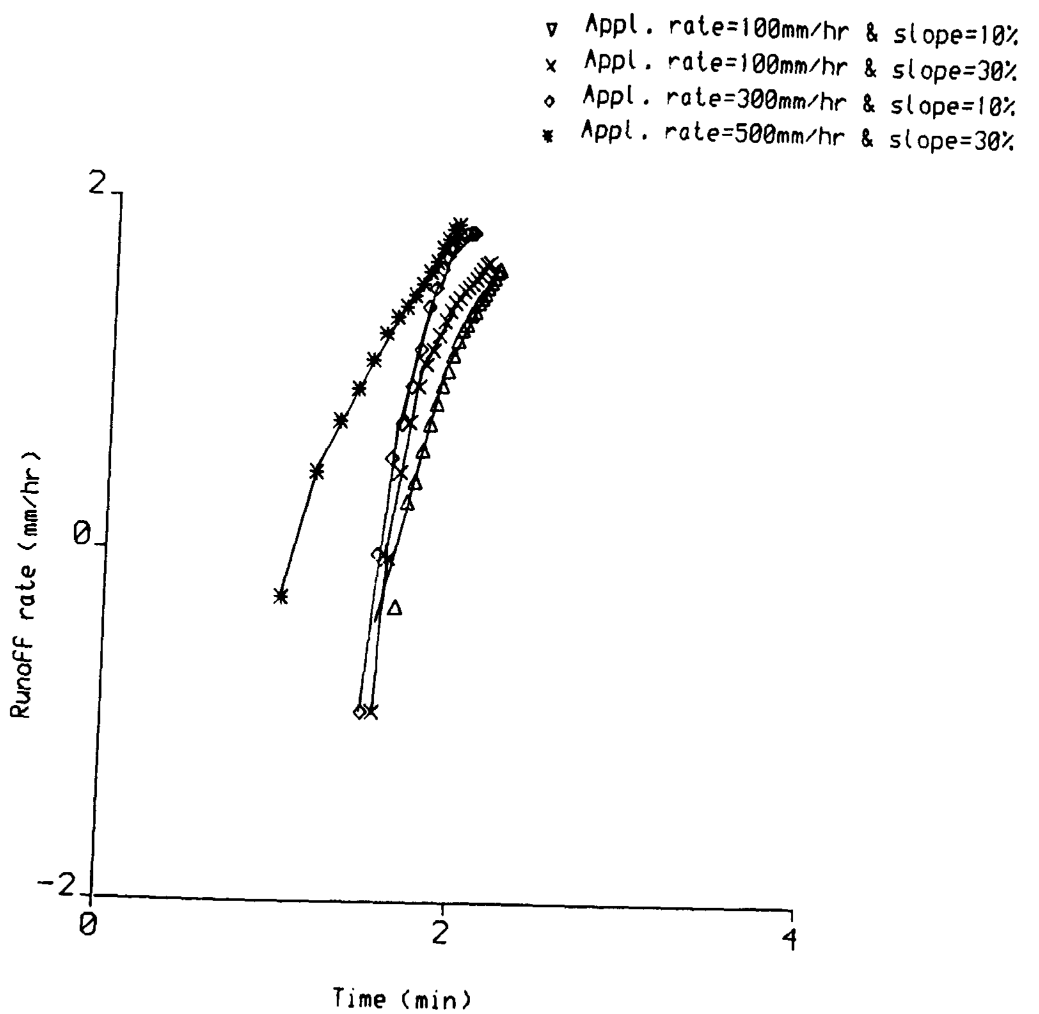


Figure 5.11 Hydrographs for soil A.

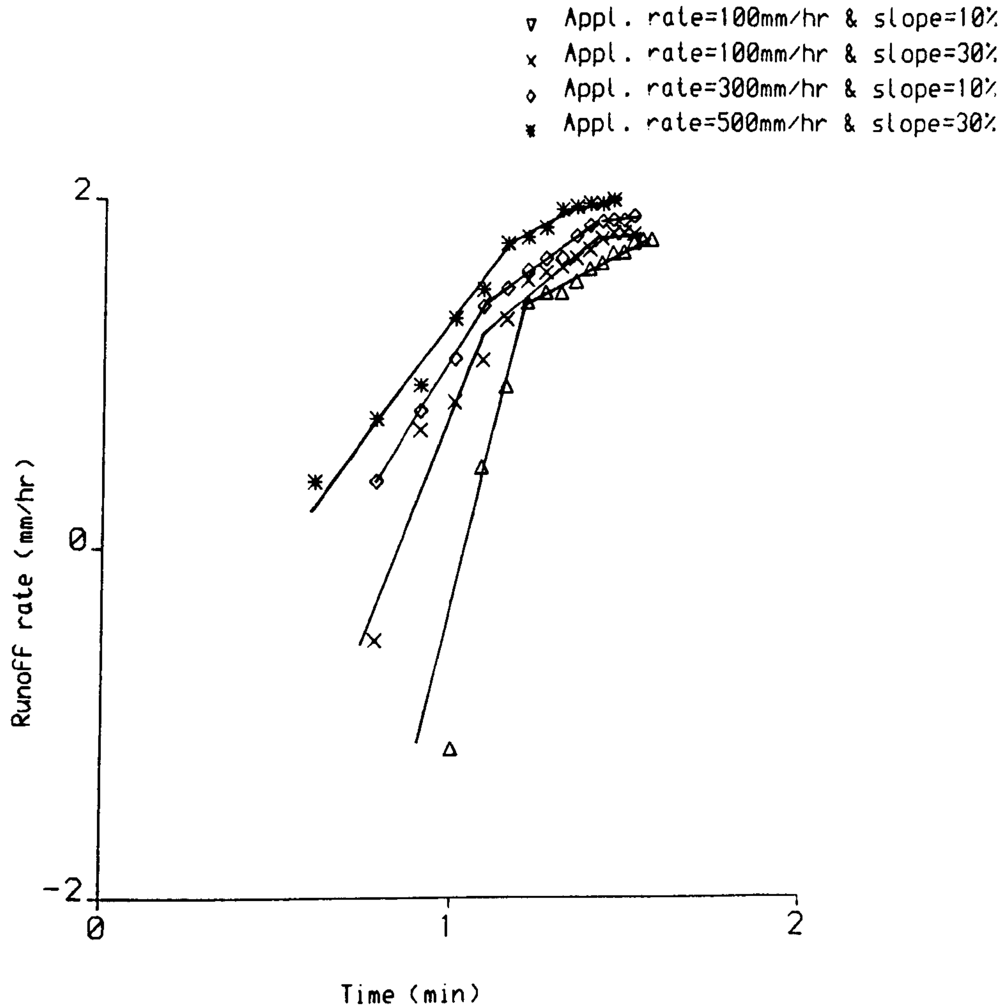


Figure 5.12 Hydrographs for soil C.

Woolhizer and Liggett (1967) for the data used in these experiments lies in the range of 14204 to 50607. This parameter of the dimensionless momentum equation was used to measure the applicability of the kinematic wave theory. Woolhizer and Liggett (1967) suggest 10 as the kinematic wave number below which a good approximation to the kinematic wave theory could not be obtained.

5.8 GOODNESS-OF-FIT STATISTICS FOR HYDROGRAPHS FITTING

The runoff curves produced by the surface runoff model will be judged statistically to show how the model performs with comparison to the measured values. It is necessary to have a measure of the goodness-of-fit of the model to the data, once the parameters have been estimated. Obviously model parameters should be selected, so that the model performs as well as possible within the constraints imposed by its structure. Various measures of goodness-of-fit have been proposed; that most commonly used is calculated (Clarke 1973) as follows :

(1) calculate the sum of squares of residuals

$$F1 = (Qm - Qp)^2 \quad . \; . \; . \; . \; . \; . \quad (5.3)$$

(2) calculate the sum of squares of deviations

$$F2 = (Qm - \bar{Q})^2 \; . \; . \; . \; . \; . \; . \quad (5.4)$$

where

Qm = measured runoff at a given time
Qp = predicted runoff at a given time
$\bar{Q}$ = mean measured runoff values

(3) calculate $R^2 = (F2 - F1) / F2$. Then R^2 the measured required.

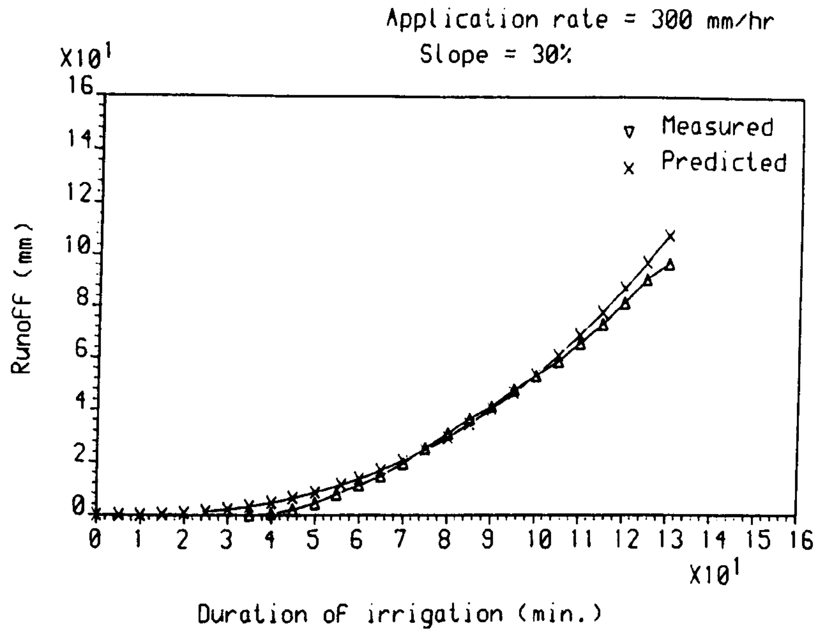
If all residuals were zero, so that the model fitted perfectly, the value of R^2 would equal 1 (or 100, if R^2 is expressed as a percentage), so that the nearer to unity the value of R^2 calculated in (3), the better the goodness-of-fit as judged by this criterion.

5.8.1 Comparison Of Model And Experiment

A comparison of cumulative measured and predicted surface runoff depths versus time are shown in figures 5.13 to 5.16. Results for soil A are shown in figures 5.13 and 5.14, and results for soil C are shown in figures 5.15 and 5.16.

A visual comparison between the measured and predicted runoff curves shows close agreement between theory and practice. The measured or predicted runoff versus time indicate that surface runoff develops in three stages; namely (1) an initial period of no runoff, (2) an intermediate stage where runoff is changing, and (3) a third stage where the rateof runoff reaches a constant value. During stage 2 only a portion of the plot is producing runoff, while in stage 3 runoff is occurring from the entire area. Since the measured as well as the predicted curves exhibit this general behaviour, this serves to verify the model in general.

Comparing measured and predicted times for the commencement of stage 2 the predicted runoff started earlier than the measured runoff. However, the difference is very small and the delay is probably due to depression storage which was not taken into account in the model. The delay increases with lower application rate as it takes longer to satisfy the depression storage before the runoff begins.



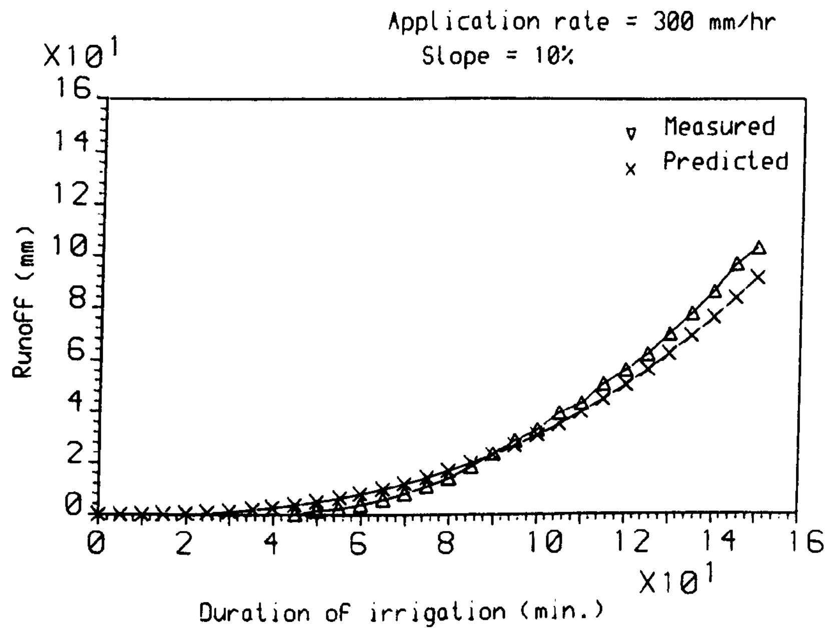
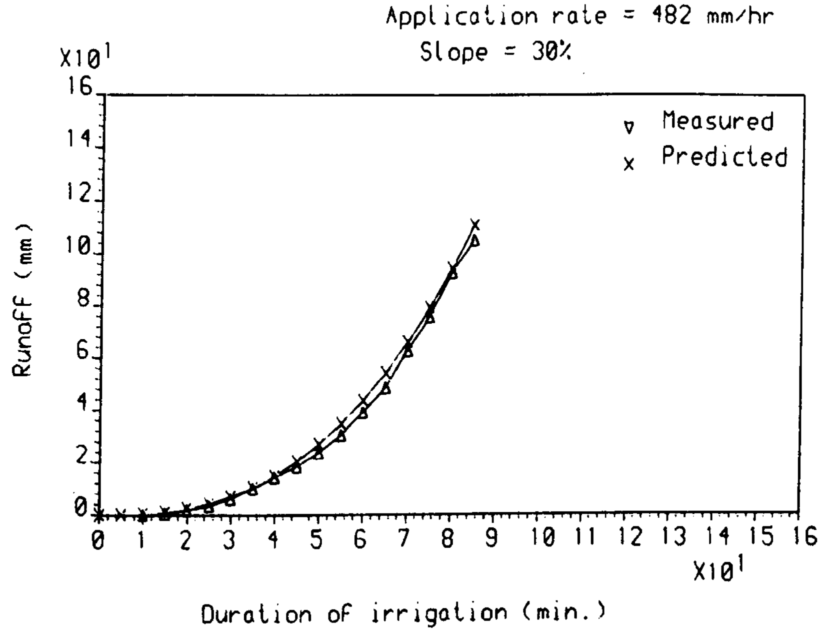


Figure 5.13 Comparison of measured and predicted accumulative runoff from soil A.



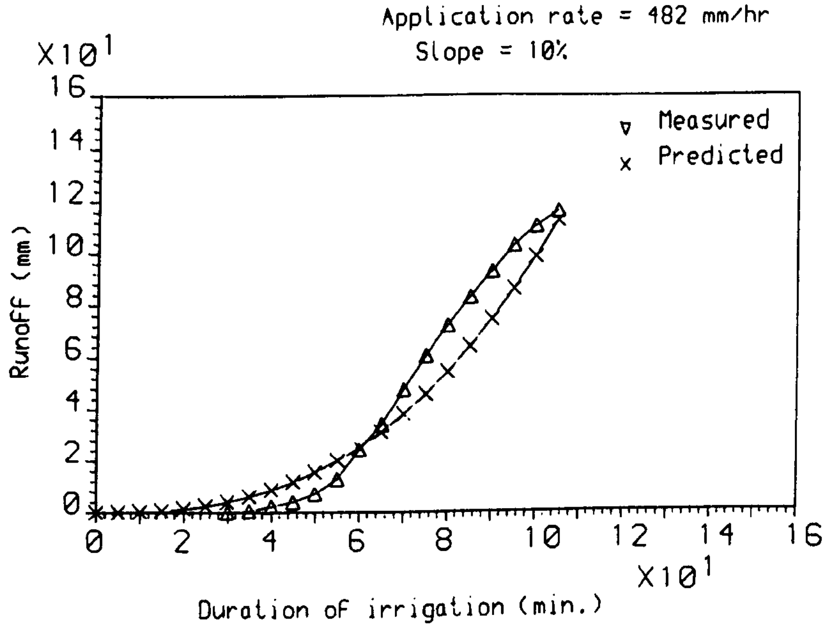
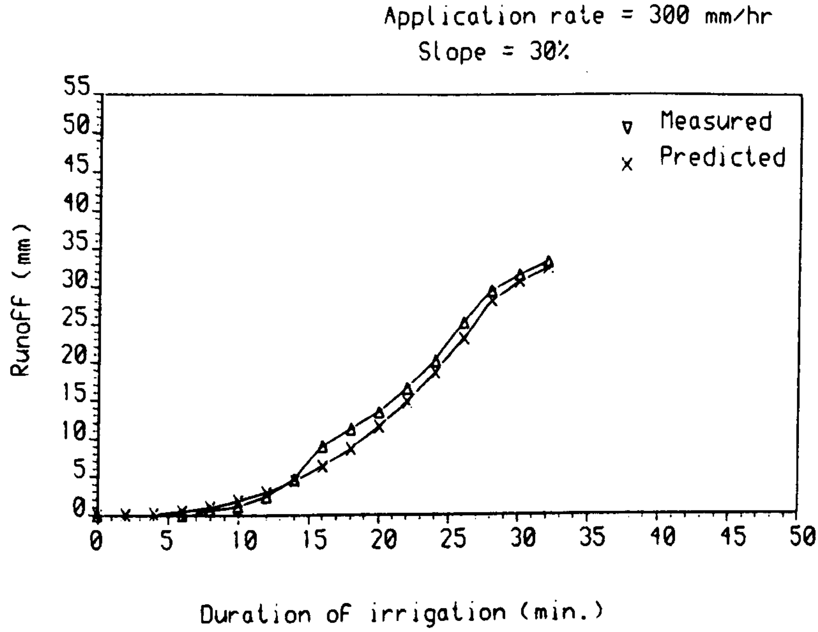


Figure 5.14 Comparison of measured and predicted accumulative runoff from soil A.



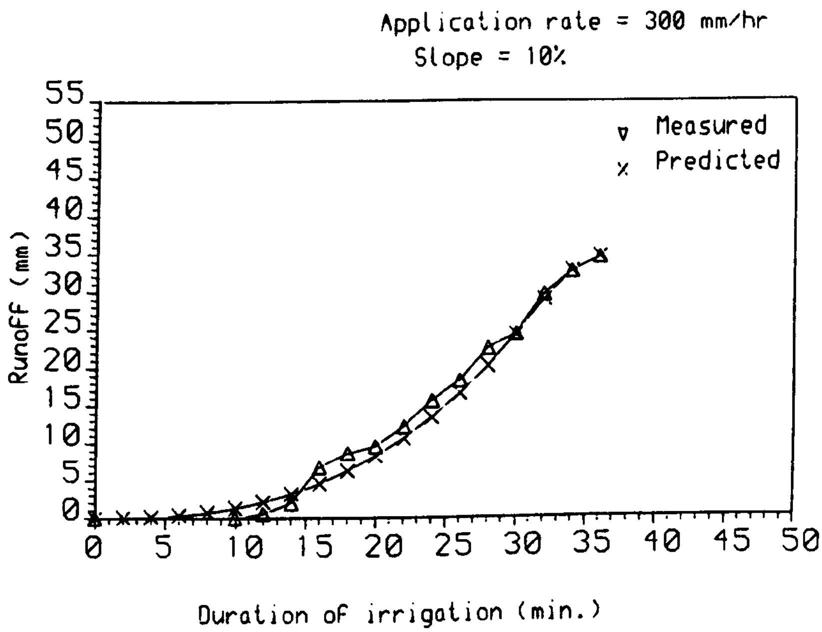
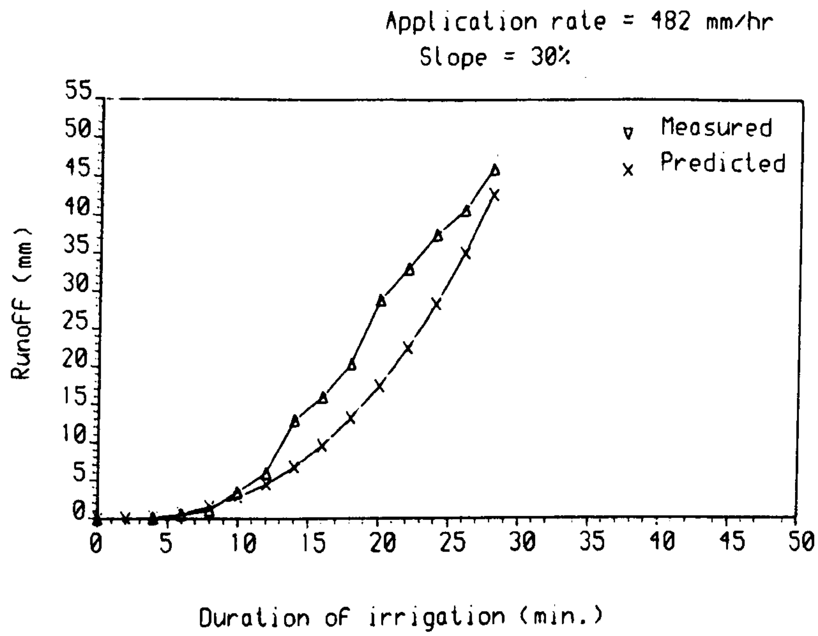


Figure 5.15 Comparison of measured and predicted accumulative runoff from soil C.



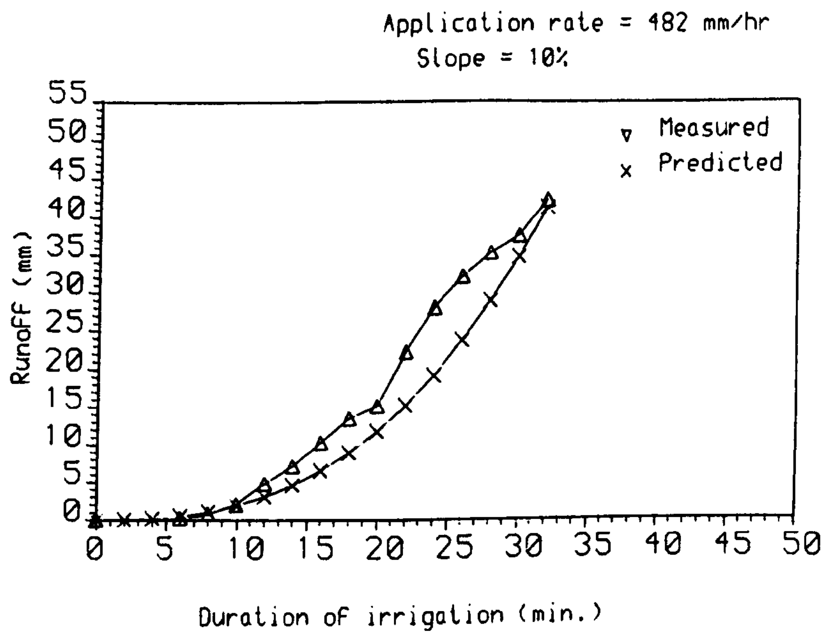


Figure 5.16 Comparison of measured and predicted accumulative runoff from soil C.

The model generally underestimates the amount of runoff and this difference is greater for soil C at the higher sprinkler intensities. This underestimate may be due to sedimentation transported by the surface runoff. The sedimentation concentration was increased with low infiltration rate as in the case of soil C, but with high infiltration the difference between measured and predicted runoff is very small.

To quantify the level of agreement between the measured and predicted surface runoff results a statistical test was made to test the model performance. The values of the goodness-of-fit between measured and predicted runoff can be seen in table 5.5.

soil	application rate (mm/hr)	slope (%)	F1	F2	R^2
	300	10	809.42	32039	0.9747
A	300	30	325.06	26541	0.9878
	482	10	2054.3	37935	0.9458
	482	30	139.40	19626	0.9960
	300	10	34.989	2695.5	0.987
C	300	30	33.123	1885.7	0.9824
	482	10	308.32	3628.6	0.915
	482	30	508.11	3927.2	0.8706

Table 5.5 Statistical analysis for hydrograph fitting.

From the figures and the values of R^2 it is clear that the surface runoff hydrographs predicted by the model are in remarkably good agreement with the measured runoff hydrographs.

This indicates clearly that the model is physically sound over the range of test conditions and has the capability of characterising the surface runoff process on small catchments such as occurs in ridge and furrow cultivations.

CHAPTER 6

Selection and Development of Interception Model

6.1 Introduction

The amount of precipitation actually reaching the ground surface is largely dependent upon the nature and the density of the vegetation cover. The crop cover intercepts part of the falling precipitation and temporarily stores it on its surfaces, from where the water is either evaporated back into the atmosphere or falls to the ground. The three main components (figure 6.1) are interception loss; water which is retained by plant canopies and which is later evaporated away or absorbed by the plant; throughfall; water which either falls through spaces in the vegetation canopy or which drips from leaves, twigs and stems to the ground surface; and stemflow; water which trickles along the twigs and branches and finally down the main stem to the ground surface.

Numerous investigators have studied the interception of water from a various standpoints ranging from the empirical approach to a mathematical analysis of equations that model the process. But relatively little attention has been given to the importance of interception from agricultural crops. The interception loss may be regarded as water loss and it is evidently this component of interception which is of most concern to investigators.

In this chapter a review of interception models is made with

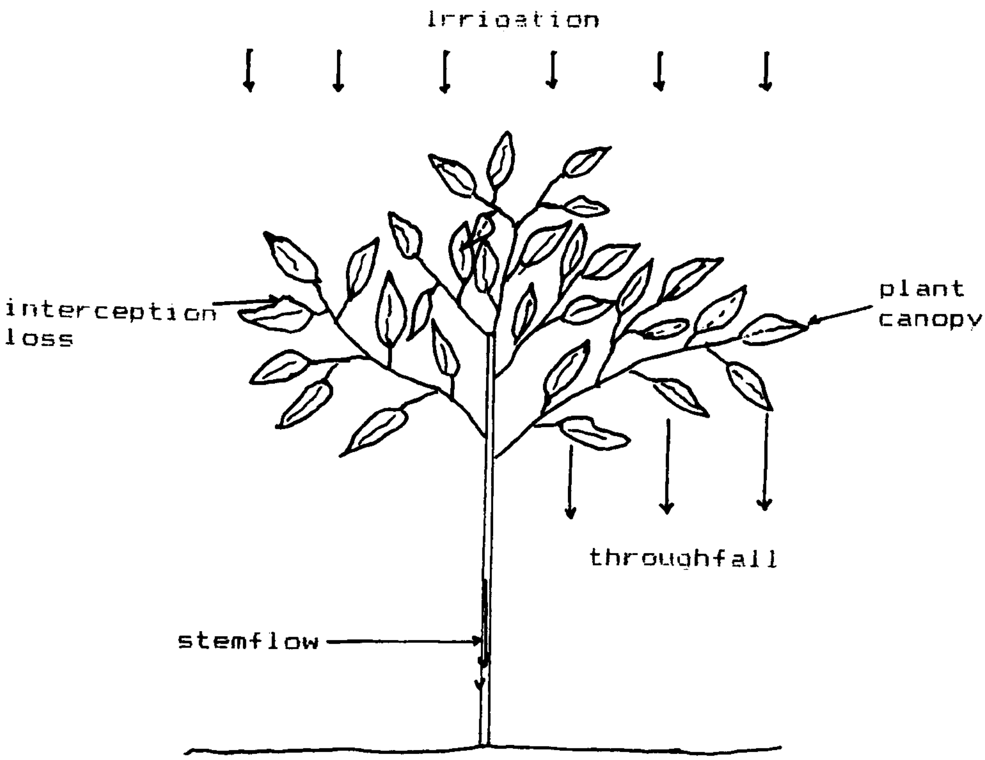


Figure 6.1 Schematic diagram of the water interception process during irrigation.

the purpose of selecting the most appropriate one that could be adapted to the requirements of this study for predicting the amount of water intercepted by the plant canopy during irrigation.

6.2 REVIEW

The fact that following a dry spell interception loss is usually greatest at the beginning of a storm and reduces with time, reflects the interaction of the main factors which affect the interception from vegetation. Of these, the most important is the interception storage capacity of the crop canopy. At first, when all the leaves and stems are dry the interception storage capacity is high and a percentage of the irrigation is stored on the plant canopy and prevented from reaching the ground. As the leaves become wetter, the weight of water on them eventually overcomes the surface tension by which it is held and, therefore further additions from rainfall or irrigation are almost entirely offset by the water droplets falling from the lower edges of the leaves.

Even during irrigation, however, a considerable amount of water may be lost by evaporation from the leaf surfaces, so that even when the initial interception storage capacity has been filled, there is some further fairly constant retention of water to make good this evaporation loss. Indeed, during long continued rains the interception loss may be closely related to the rate of evaporation (Ward 1975)

Most of the simple equations which have been devised for calculating interception are based on the principal factors affecting it. The general form for the total precipitation budget in a vegetated area may be expressed by the equation :

$$RG = Dr + Pt + Cs + E \quad . \quad . \quad . \quad . \quad . \quad (6.1)$$

Where:

RG = gross rainfall rate (mm/hr)
Dr = water draining from the canopy (mm/hr)
Pt = free throughfall
Cs = water stored on the canopy (mm)
E = water evaporated from vegetative surface (mm/hr)

Two definitions of interception loss exist : one regards the interception loss as the amount of irrigation water stored on the crop canopy and subsequently evaporated; the other regards the interception loss as that portion of irrigation were retained on the plant canopy, which is evaporated over and above that which would normally be transpired had there not been intercepted water. The former is called gross interception loss and the latter is termed net interception loss.

Most of the work done on interception in recent years was being done on trees. There have been several different approaches to estimating water intercepted by trees. One approach is to use dynamic models to predict the quantity of water intercepted during rain, such as Rutter et al (1971,1975), Calder (1976), Rutter and Morton (1977), and Massman (1980,1983). The other approach is empirical, which uses logarithmic or exponential regression equations to fit observed data. this approach was taken by a number of investigators, such as Zinke (1967), Jackson (1975) and, Rao (1987).

Leonard (1967) described the theory of the interception process in this relationship :

$$Is = Sc + Ra \cdot E \cdot t \quad . \quad . \quad . \quad . \quad . \quad (6.2)$$

where:

Is = gross interception loss and expressed in terms of mm water per unit ground projected area of the canopy.
Sc = the water stored on the canopy in mm per projected area of the canopy.
E = evaporation rate in mm/hr during the storm from the evaporation surface.
Ra = the ratio of evaporating surface to the projectional area.
t = the duration of the storm in hr

Rutter etal (1971) developed a model to calculate the interception components. He assumed that all the rain not passing directly through the canopy would be stored on the foliage and would be subjected to the drainage process according to the relationship :

$$Dr = kl \exp(Bl\ Cs) \quad . . . . . \quad (6.3)$$

The quantity of water stored on the plant canopy can then be calculated by the equation :

$$Cs / t = Q - Dr \quad . . . . . . \quad (6.4)$$

$$Q = (1 - Pt)\ R \quad . . . . . . \quad (6.5)$$

where:

Dr = drainage rate from the canopy (mm/hr).
Q = net input of water to the canopy storage (mm/hr).
R = application rate (mm/hr).
Cs = canopy storage capacity , or water stored on the plant during irrigation (mm).
Pt = free throughfall.
kl , Bl are drainage constant parameters.

Jackson (1975) developed a relationship to predict the gross interception loss (i).

$$Is = 0.8528 + 0.5419 \ln RG \quad . . . . . . \quad (6.6)$$

where:

RG = gross rainfall rate (mm/hr)

Massman (1980) developed this relationship for water storage on forest foliage :

$$Dr(t) = Is(t)\,(\exp(O\,(Sc/Cs))-1)/\,\mathrm{EXP}(O)-1) \quad \ldots\ldots (6.7)$$

where:

Cs = maximum storage capacity (mm).
Sc = canopy storage, water stored on the plant after irrigation and leaf drip ceased (mm).
Is(t)= interception intensity (mm/hr)
O = constant, depends on tree species and meteorological conditions.

The canopy storage capacity is important in the interception process. Leonard (1967) stated, but did not substantiate that the amount of water retained by the leaf or its storage will be dependent on leaf area, leaf area index, storm intensity, and surface tension forces resulting from leaf surface configuration, liquid viscosity and mechanical activity. A survey of U.S.A. interception studies by Zinke (1967) showed that values for interception storage capacity ranged from 0.25 to 9.14 mm per unit vegetation area.

Despite the long history of experimental investigation of interception there remain conflicting views about its quantitative significance in the water balance of a catchment area (Ward 1975). The interception losses from vegetated surfaces will become important when their ratios to the irrigation are high. Calder (1979) and Gash et al (1980) have reported that there could be a reduction in water yield to almost a zero level after afforestation of grasslands. This is because of high interception losses of rainfall from forests than from short vegetation. Rao (1987) reported that the interception loss from cashew trees was about 31% of the storm rainfall.

There are a number of factors which can change rate of interception for a crop. These factors include canopy density, the aerodynamic resistance to this transfer of water vapour, and the rates of change of leaves drip and evaporation of water with respect to canopy storage. Herwitz (1987) reported that raindrop detention increases linearly as a function of branch inclination on branches that are initially dry, and on branches that have been thoroughly wetted, this increase in raindrop detention with branch inclination is best expressed as a logarithmic function. Hall (1985) found that drainage parameters are likely to have a greater effect on the interception ratio.

There are investigators who have measured the water interception for agricultural crops. Appelmans et al (1980) reported that the amount of water intercepted by sugarbeet was a function of rainfall intensity, when the rainfall intensity is 27.5 mm/hr the interception loss was 3.6%, but the interception loss was 15.9% when the intensity was 5.8 mm/hr. Morgan (1985) measured the simulated rainfall volume reaching the ground surface in the field under corn and soybean canopies. He found that the rainfall volume reaching the ground surface decreased with the increase of canopy cover only slightly until 50% cover was reached, and then more quickly to reach about 40% of that open ground with 90% cover. He concluded that rainfall interception is not directly proportional to percentage cover. Morgan et al (1986) have reported that the canopy interception increased in direct proportion with the increase of canopy up to 20% cover for Brussel sprouts and potatoes. Also they found that further increase in canopy cover caused interception to increase at a decreasing rate, so that with 40 to 50% cover only 22% of simulated rainfall was intercepted by Brussel sprouts, and 21% with 27% cover by potatoes. The influence of crop canopy interception and stemflow on the water distribution in the crop root zone has been discussed in chapter 2, section 2.9.

There have been several different approaches to estimating water intercepted by agricultural crops. The majority consist of regression equations between gross interception loss and rainfall. These approaches provide little in sight into the process of interception and the regression coefficients are specific to particular stands of vegetation and storm regimes (Aston 1979). These parameters may also differ with different time intervals in analysis. furthermore, they do not allow for continuous variation in evaporation or rainfall, nor do they account for the influence of growth and development of plant communities (Aston 1979).

The model developed by Rutter et al (1971, 1975) for trees describes the interception in terms of both the structure of the plant and the climate in which it is growing; also being being physically based it has potential for application in all areas where there are suitable data (Gash and Morton 1978), and is quite flexible with the evaporation rate. The model was first developed for the prediction of interception loss in pine canopies, but many researchers have used it to predict the amount of water intercepted by the canopy for different type of trees with different sizes.The model is easy to use and flexible for future work modification. The agricultural crops are quite different to trees in many respects, but may be not so different in their interception behaviour and patterns.

Considering the requirements of this study which includes variable water application rates, Rutter et al (1971, 1975) would appear to be most suitable for adoption to predict the amount of water intercepted by agricultural crops.

6.3 EQUATION DEVELOPMENT

The water intercepted by the plant canopy is regarded as a store of water replenished by the rainfall and depleted by evaporation and dripping (Rutter 1975). To calculate the amount of water intercepted by the canopy cover and stored on the plant. The equations for that were first developed by Rutter et al (1971) to describe the interception loss of rainfall in terms of both the structure of the forest, and the climate in which it is growing.

The process of interception is described by the continuity equation which are for a canopy of vegetation including the stems are described by the following equations (Rutter et al 1971, 1975) :

$$-\ dCs / dt = Dr - Q \qquad \ldots\ldots (6.8)$$

$$Dr = kl \exp (Bl.Cs) \qquad \ldots\ldots (6.9)$$

$$Q = (1-Pt)\ R - E \qquad \ldots\ldots (6.10) \quad \text{for } Cs \geqslant Sc$$

$$Q = (1-Pt)\ R - E \cdot Cs/Sc \qquad \ldots\ldots (6.11) \quad \text{for } Cs < Sc$$

where:

Dr= rate of drainage from a wet canopy (mm/hr)
t = irrigation time (hr)
Cs = canopy storage : the water stored during the irrigation on the crop canopy per unit ground projection area (mm).
Q = net input of water to canopy storage (mm/hr).
Pt = free throughfall coefficient : the proportion of the rain which falls to the ground without striking the canopy.
Sc = the canopy storage capacity : the amount of water left on the canopy, when irrigation and throughfall had ceased (mm).

kl and Bl are constant drainage parameters.

To apply the equations to compute the interception, or the amount of water stored on the crop canopy,and throughfall, the drainage parameters have first to be determined, first for the plant, still neglecting evaporation.

combining equations (6.8) and (6.9) will give :

$$- dCs / dt = k1 \exp(B1\ Cs) - Q \quad . \quad . \quad . \quad . \quad . \qquad (6.12)$$

integrating d Cs from to to t gives :

$$Cs = (\ln Q + B1(Cs+tQ) - \ln(k1 \exp(B1(Cs+tQ)) - k1 \exp(B1 Cs) + Q)/B1) \quad .(6.13)$$

Where:

CS = the amount of water (mm) stored on the plant canopy during irrigation at time t.

Equation (6.13) can be used to calculate the amount of water stored on the plant canopy during irrigation at any time.

The assumptions made for this calculation are :

(1) the evaporation rate during irrigation is neglected. The experiment work was carried out in the laboratory and the temperature during the experiment was low.

(2) the drainage rate is set to zero when $C<S$ (Rutter 1971,1975).

The canopy storage capacity (S) is defined by Rutter et al (1975) as the value of C when D falls to an arbitrary value of 0.002 mm/min after the cessation of the storm event.

6.4 MODEL OPERATION

To calculate the interception a computer program (INCEPT) was written in fortran -77 on VAX /VMS version 4.6. This program can be combined as a subroutine to the main program (SROFF), so that surface runoff can be calculated taking account of the interception loss. A flow chart showing the various steps of the computational logic utilized in the model is shown in figure 6.2. A printout of the program can be seen in appendix A.2 (table 2).

The program operates by using screen management routine and

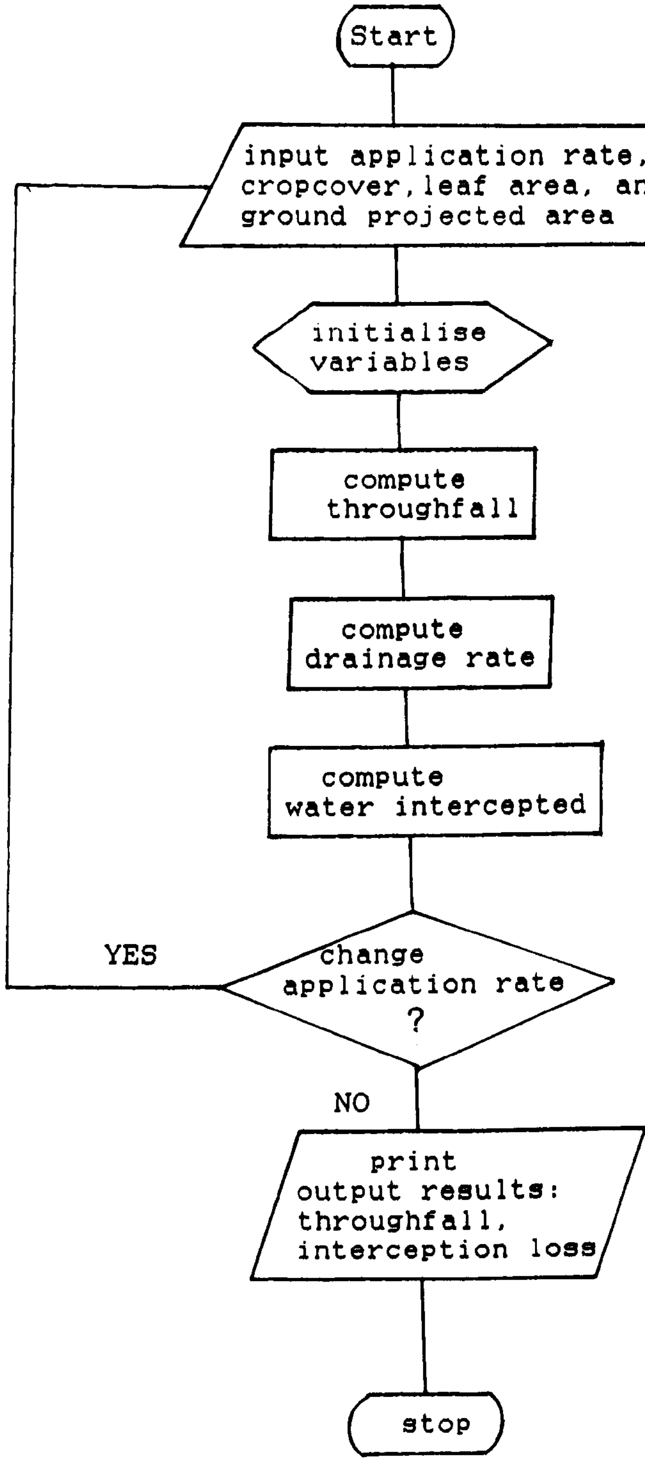


Figure 6.2 Flow chart of program INCEPT.

reading data. The interception loss can be calculated at the chosen time increment. This computation process is repeated when the input is changed, and the required time to run the program is dependent on the selected time increment and the maximum simulation time required.

The input data utilized by the program are application rate, and drainage parameters. The output is throughfall and the interception loss, and may be used as an input into the main program (SROFF).

CHAPTER 7

INTERCEPTION MODEL VALIDATION

7.1 INTRODUCTION

To validate the interception model (incept) experiments were designed and carried out to compare the measured data obtained with the data predicted by the model. A range of application rates were chosen, so that differences could be expected in both experimental and simulated data for comparison.

The effects of crop canopy interception, stemflow, and leaf drip are also examined experimentally in a soil tank to see how they influence both runoff and infiltration into the crop root zone with different water application rates and different cultivation practices.

7.2 EQUIPMENT

Materials required for the experiments included a sand tank, a small artificial plant, a soil, and spray system to apply the different application rates.

The spray system used was the same system used for the experiments as described in chapter 5. The application rates used were 100, 300, and 482 mm/hr.

7.3 MEASUREMENTS

This section describes the measurements of stemflow, throughfall, free throughfall, and canopy storage. Also the findings obtained from these measurements in the laboratory using the three application rates is presented and discussed in relation to the plant canopy being used in these experiments.

Plant characteristics

An artificial plant was chosen in preference to a real plant because it did not change its characteristics during the experiments. The selected plant is similar to a small potato plant. The artificial plant was made of silk for the leaves, and the stem and branches were made of plastic. Table 7.1 shows details of its basic interception characteristics.

Attribute	Value
Ground cover	27 %
Plant height	0.5 m
Leaf area	0.0602 m2
ground projected area	0.048 m2
leaf area index	1.25

Table 7.1 Artificial plant characteristics.

Stemflow

Irrigation water flowing down the plant stem was measured by using a technique similar to the one used by Noble and Morgan (1983) by mounting the plant in plastic tube (figure 7.1), the tube served to hold the plant in a vertical position and to channel the stemflow into a cylinder for measurement. The stemflow was measured every minute until a steady state flow was reached. Each experiment was repeated three times for each of the three application rates.

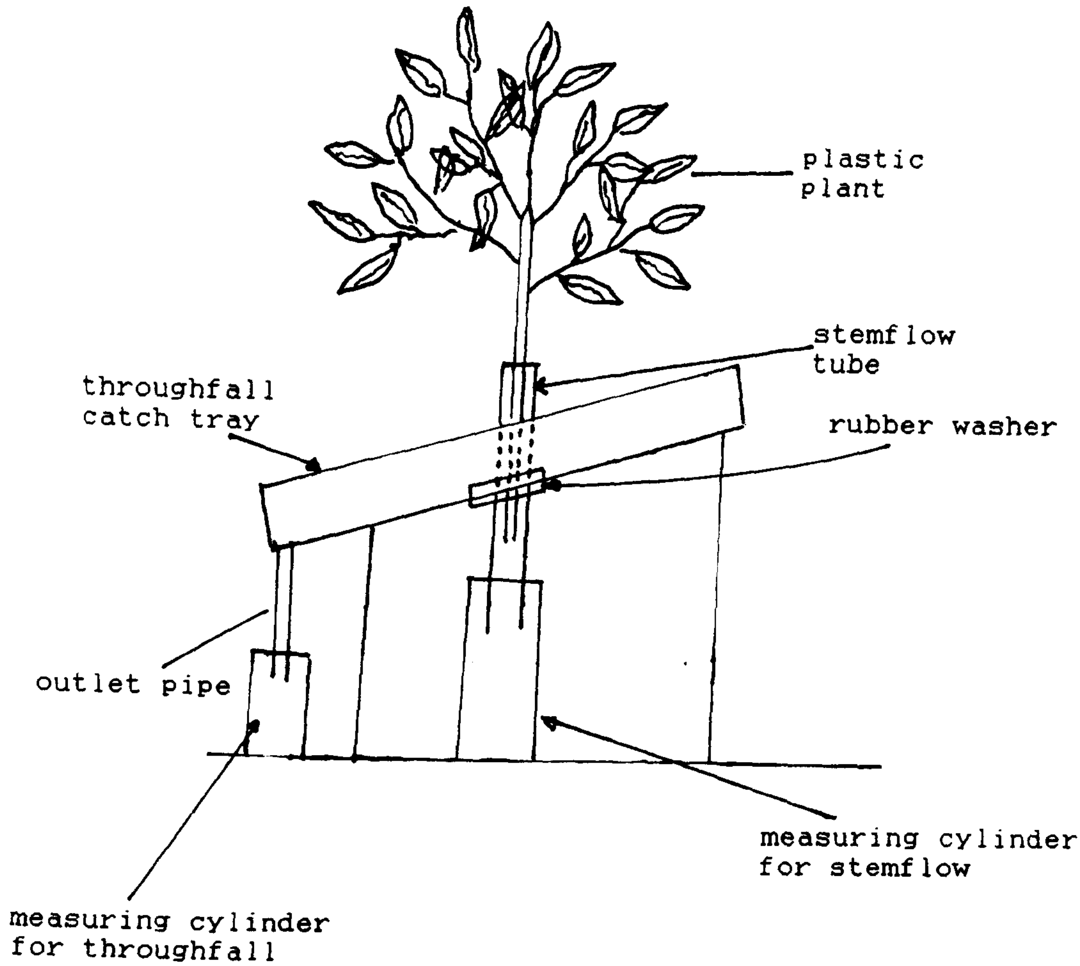


Figure 7.1 Apparatus for measurement of stemflow and throughfall.

The measurements were made for each irrigation intensity for duration of 10 minutes of irrigation. The stemflow was expressed as a percentage of the water that would be received on an area of ground equal to that of the projected ground cover. The measurements are shown in table 7.2

application rate (mm/hr)	stemflow (%)
100.0	35
300.0	25
482.0	18

Table 7.2 mean stemflow measurements.

Throughfall (TF)

The total throughfall measurement was carried out by positioning the plant vertically beneath the spray system in the middle of 150 400 mm catch tray (figure 7.1). When water was applied , the total throughfall (which includes leaf drip, and free throughfall) was received on the surface of the tray. It was then channelled down a slope into a pipe connected to a plastic tube, and into a cylinder for measurement every minute. The tray was positioned at a slope sufficient to allow the water received on the tray to drain off through the pipe into the collecting cylinder. The water was applied until a steady state flow was reached. The mean values of the throughfall from three replications for every application rate for 10 minutes irrigation application are shown table 7.3

application rate (mm/hr)	throughfall (%)
100.0	57.0
300.0	71.0
482.0	79.0

Table 7.3 Mean throughfall measurements.

Another set of experiments were carried out to see how water was distributed beneath the plant canopy. That was carried by placing a row of plastic cups (8 cups) of 67 mm in diameter beneath the plant, where 25 mm of water was applied for each application rate, and the throughfall (leaf drip+ free throughfall) was collected and measured.

The leaf drip from the plant at the soil surface was observed during the experiment and was not uniform under the plant canopy and, more water was drifting towards the outer edge of the plant canopy.

Free throughfall (p)

The ground projection of the plant area was determined by taking a vertical photograph from above the plant at height of 2 m. This is the same technique as was used by Hall (1985). Before taking the photograph a wooden frame divided (plate 7.1) into 20 mm square sections was placed directly above the plant. The number of squares in which the plant visible then gave an estimate of free throughfall, and the total leaf area of the plant canopy was measured using a leaf area meter (planimeter).

The free throughfall coefficient was determined for the

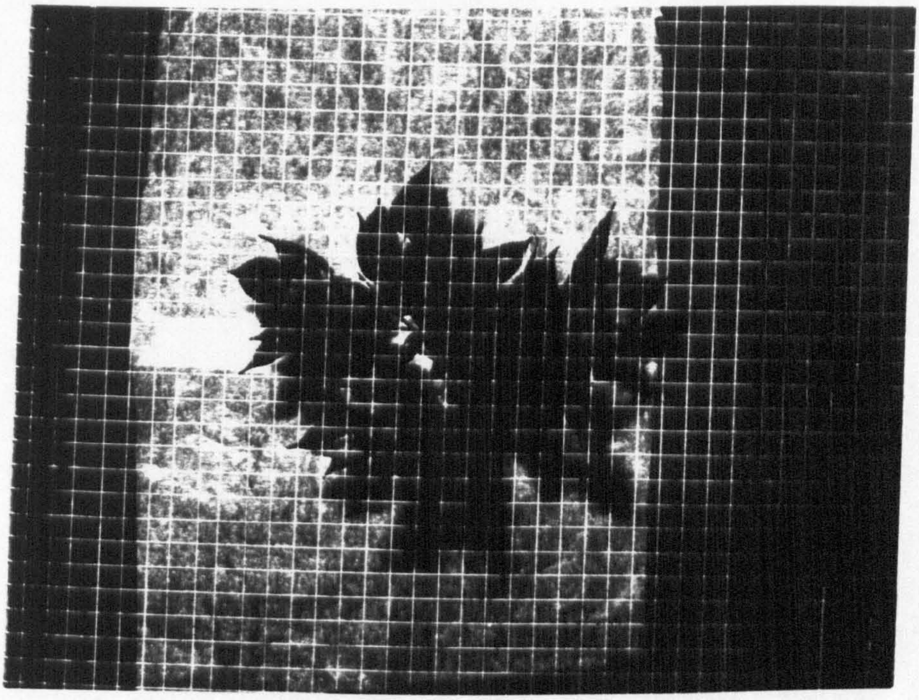


Plate 7.1 A photograph used to estimate free throughfall.

plant by using the photographic method. This was 0.25.

The interception loss (c)

The amount of water intercepted and stored on the canopy (C) during irrigation was measured. To determine this an electronic balance was used to weigh the plant at certain time during exposure to irrigation (figure 7.2). This was carried out by covering the electronic balance with a plastic container to prevent any water coming onto the balance from any direction. The plant before each experiment was placed on small base on the balance through small hole on the top of the container (plate 7.2). The small base served to hold the plant in a vertical position on the balance. A rubber washer was used at the top of the hole to prevent the stemflow and any water coming inside the container. Before the irrigation started the balance was levelled to zero and then the water applied. The accumulation of simulated irrigation on the exposed plant was recorded every 10 seconds until the canopy saturation was reached. The readings were taken through a transparent window made in the container .The average of water intercepted by the plant canopy under each application rate and The time required to reach the maximum capacity at three irrigation intensities is shown in figure 7.3.

It was found that the highest water storage capacity (Cmax.) was recorded with the 482 mm/hr irrigation application . The maximum amount of water stored occurred when the rate of irrigation interception equalled the drainage rate, neglecting evaporation. It followed that the maximum water storage capacity would increase with an increase in water application intensity. This result agrees with the findings by Aston (1979).

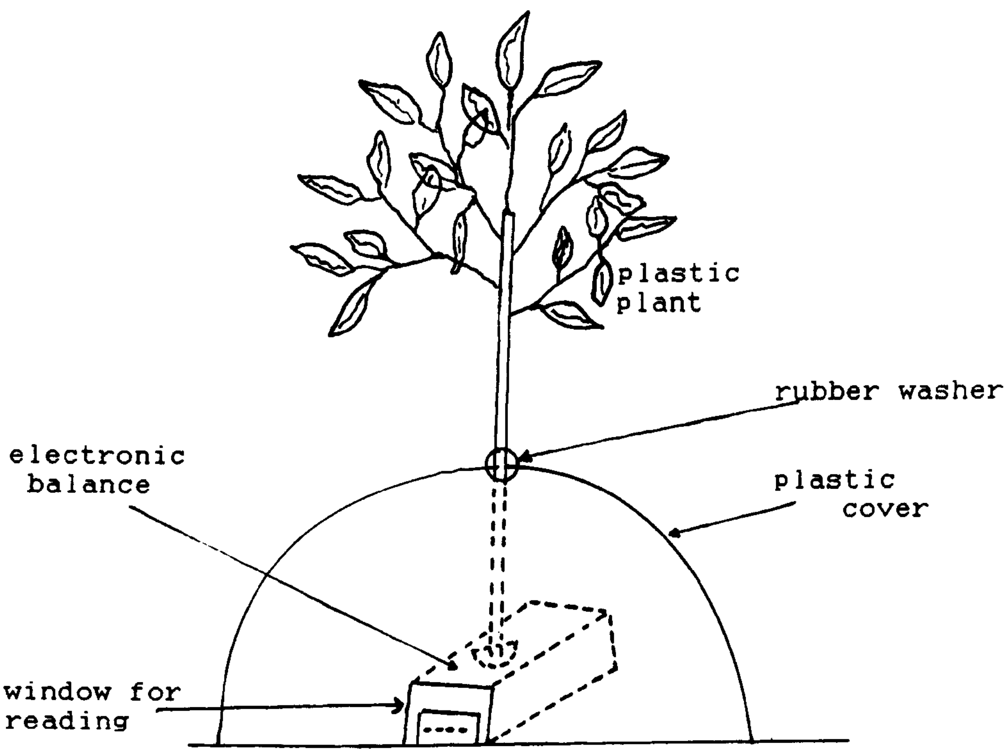


Figure 7.2 Apparatus for measurement of canopy storage capacity.

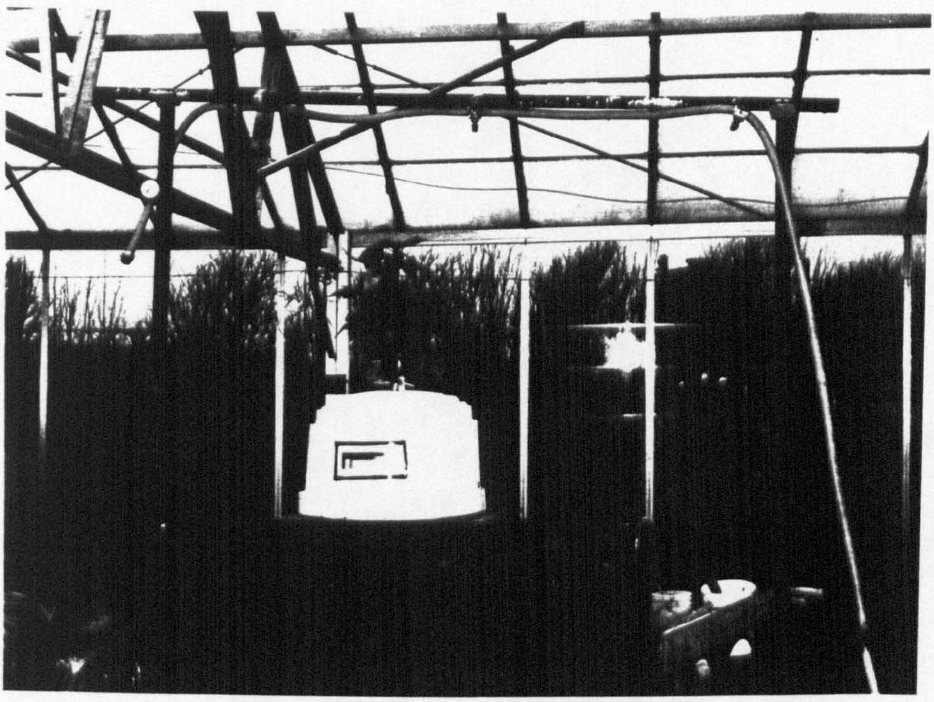


Plate 7.2 Apparatus for measurement of water stored on the plant canopy during irrigation.

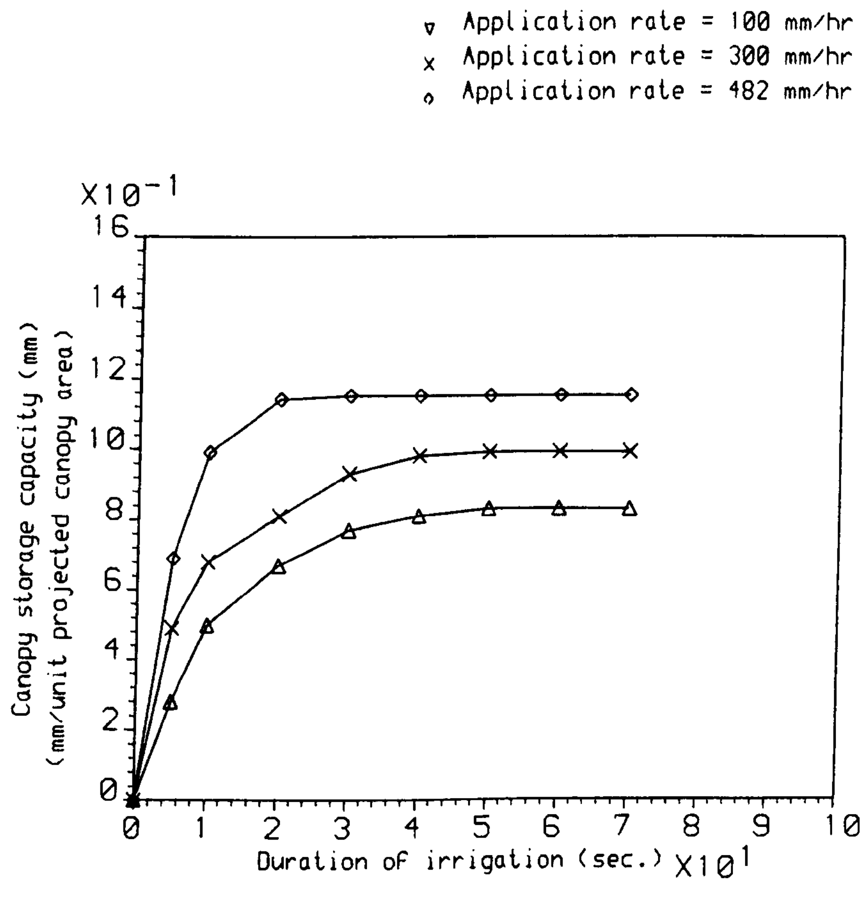


Figure **7.3** Measured water stored on the plant canopy during irrigation.

The amount of water intercepted by this plant is not very high and may be consider unimportant from an irrigation point of view. This is probably due to the small cover provided by the artificial plant, and this could be changed with more populated area of plants.

The leaf drainage was determined immediately after the irrigation ceased by recording the decrease in water weight every 10 seconds, for the first 3 minutes, and every 1 minute for 10 minutes, and then every 5 minutes for 30 minutes.

The drainage of water from the canopy was determined (change in weight with time) after the irrigation had ceased, as shown in figure 7.4. Which shows the decrease of the amount of water held on the plant canopy.

To determine the drainage constant parameters, the observed drainage rate expressed as the rate of drainage per unit ground projection area with the water retained on the plant during irrigation were used in a simple iterative least squares logarithm. Which assumed that the measured drainage was in the form :

$$Dr = k1 \exp(B1\ Cs) \quad \ldots\ldots\ldots\ldots \quad (7.1)$$

The mean values of k and, b for the three application rates are 0.41 and 5.7, respectively. These values will be used in the model calculations.

The drainage of water from the canopy was determined after irrigation had ceased for each application rate. From the results shown in figure 7.4 the final drainage rate from the canopy was nearly equal for all three irrigation intensities. The drainage experiments demonstrated that the drainage rates of

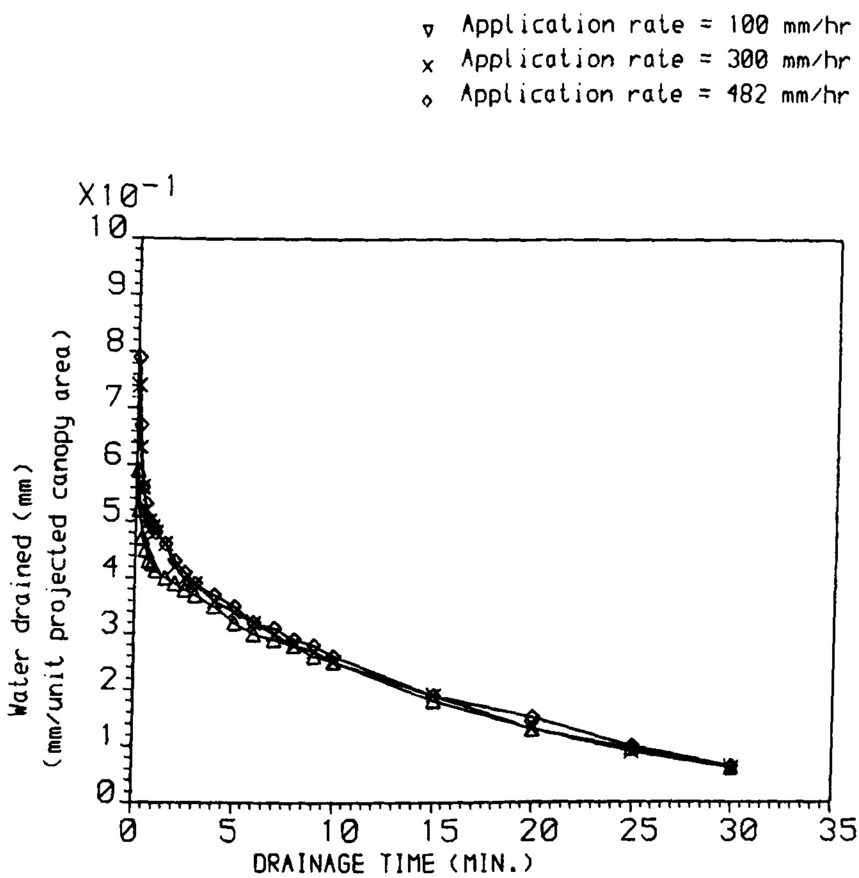


Figure 7.4 Measured water drained from the plant canopy(including stemflow) after irrigation has ceased.

the plant canopy are well described by an exponential function of the form of equation (7.1). The drainage experiments also, showed that all significant drainage had ceased at a mean storage of 0.38 mm after 3 minutes of drainage. This value can be equated to the canopy storage (S), defined as the amount of water stored on the canopy (including stems) when irrigation and drainage had ceased in still air, Zinke (1967). Aston (1979) assumed the interception storage (S) to be the amount of water retained on the canopy after a drainage of 2 minutes after irrigation had ceased.

7.4 COMPARISON OF MODEL AND EXPERIMENT

A comparison between measured and predicted results can be seen in figures 7.5. From the curves, it can be seen that the agreement between the simulated and the measured results is good initially, but the model tended to overestimate C as the maximum was approached. This overestimation could be related to the accuracy of the sensitive drainage relationship. Small errors in the slope will give significant variation between actual and simulated results, Aston (1979). Another reason for the variation could be related to the assumption that evaporation is set to zero during irrigation. The interception loss predicted by the model is relatively in good agreement with measured results.

7.5 CONCLUSION

The interception of water studies by crop canopy were undertaken on one plastic plant under different irrigation intensities. The results have been used to validate the

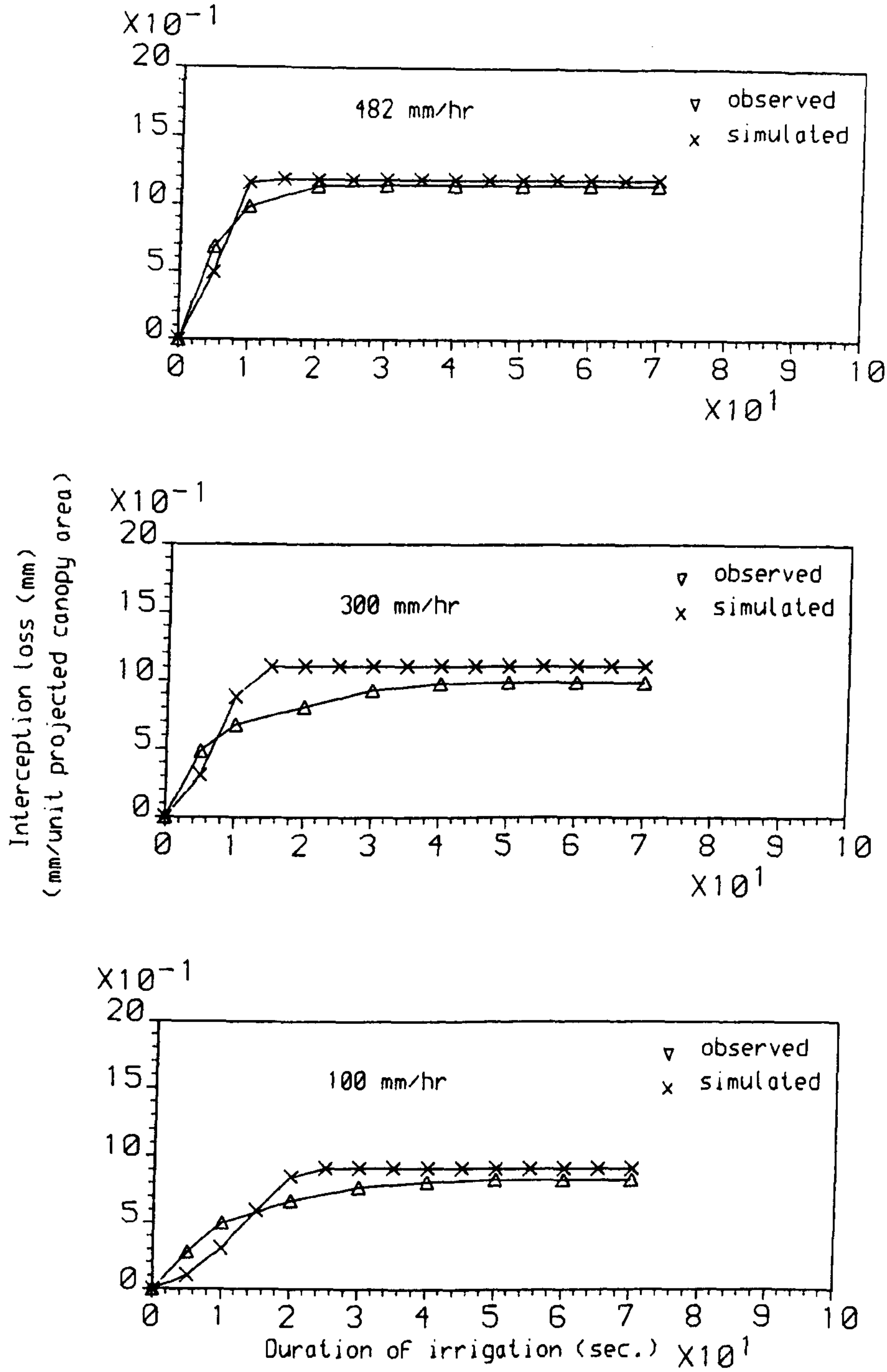


Figure 7.5 Comparison of measured and predicted values of interception loss at three different water application rates.

interception model to compute crop interception loss during irrigation. In general the model prediction is in good agreement with measured results. The output data of the interception model can be used as an input data file into the surface runoff model.

7.6 WATER DISTRIBUTION AND RUNOFF MEASUREMENTS

A laboratory experiment was also designed to investigate the effects of throughfall, stemflow, and cultivation practices on the water distribution in the crop root zone.

A soil tank (figure 7.6) was designed with a transparent side (glass) to enable observations and measurement of water movement in a soil profile to be made . The rear of the tank was used for collecting runoff through holes drilled for this purpose, and the soil could also be removed from the rear of the tank after every experiment for drying. The tank was designed with the dimensions of 1.2 m long, 0.15 m width, and 0.7 m deep.

Soil used in previous experiments was first air dried and then sieved using 12.5 mm mesh sieve. The soil was then placed in the soil tank, and uniformly compacted by a metal roller until the ridge was constructed centrally in the tank. The average bulk density was 1.1 g/cm^3, ridge sideslopes of 10% and 30% where prepared with each application rate respectively. These two slopes were chosen because they were used in previous experiment work and so their influence of infiltration and water distribution could be examined.

Before irrigation began two plastic hoses were attached to each side of the soil tank to collect the surface runoff from the

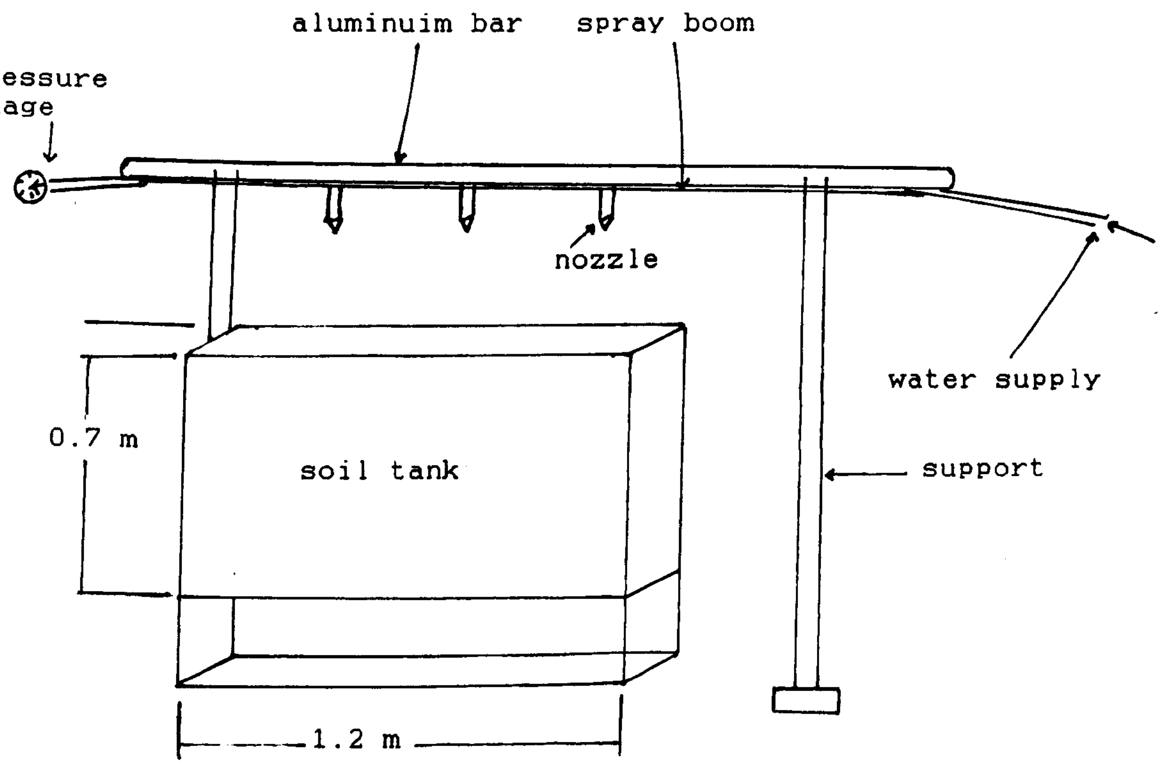


Figure 7.6 Schematic diagram of the soil tank with spray system.

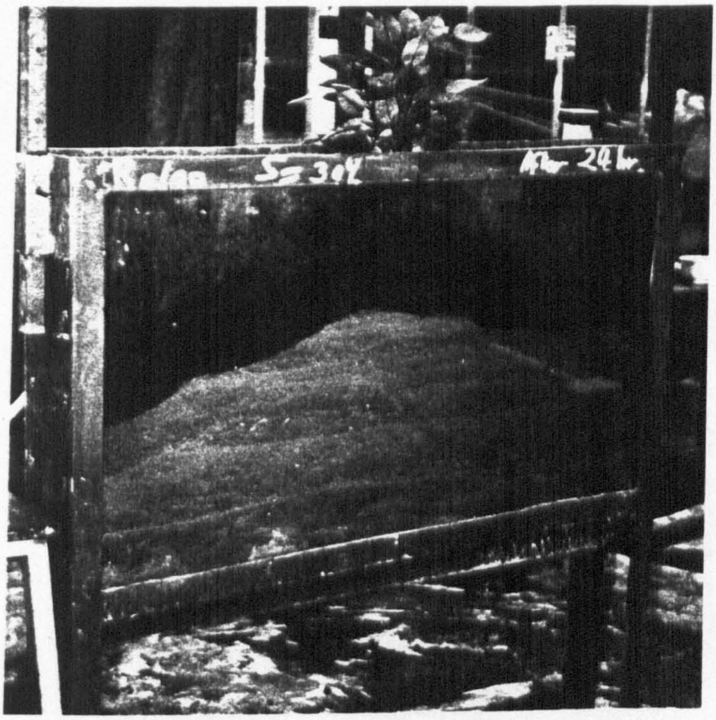
water application from the ridge side, two cylinders were used to collect water for measurement each minute. The plastic plant used in the interception validation experiment was positioned vertically at the centre of the ridge (plate 7.3). The spray boom was then set above the plant at a height appropriate to the required application rate (see section 5.2).

For each application rate with different soil slopes each experiment was repeated three times. The depth of water applied each run was 50 MM. The surface runoff was recorded every minute, and wetting patterns in the soil profile were measured along the soil tank 24 hours after irrigation (plates 7.3 and 7.4). The wetting pattern measurements were taken horizontally along the ridge profile at 100 mm increments, and 50 mm increments below the ridge top. The soil was then removed from the tank and replaced by another air dried soil for the next test.

7.7 SOIL WATER DISTRIBUTION

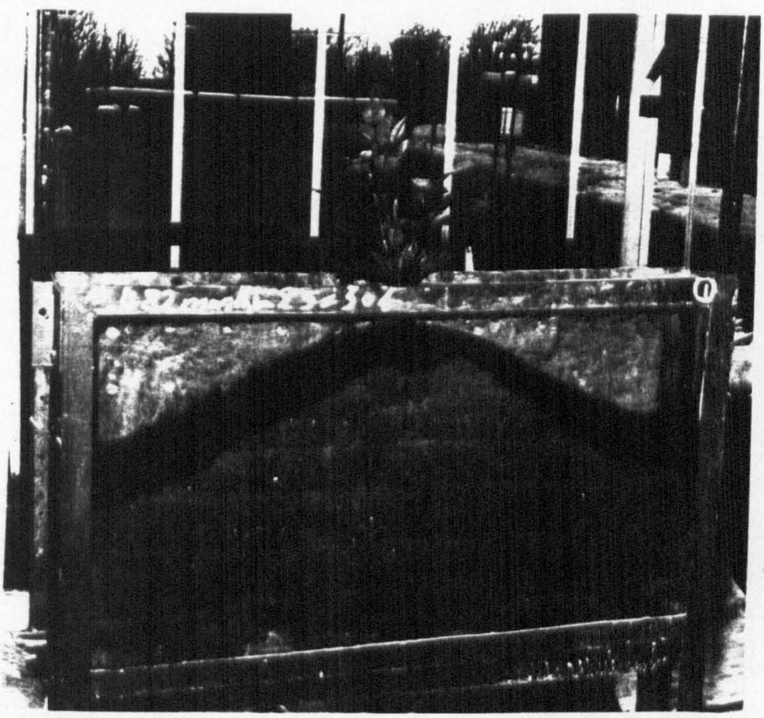
The prime objective of these investigations was to examine the effects of canopy interception and slope on distribution of irrigation water at the soil surface and in the crop root zone. Although runoff was also measured. The high application intensity of 482 mm/hr produced runoff on both slopes. The reason for little or no runoff was because the application of 50 mm was relatively small.

The runoff measured was not very high in comparison to the amount of water applied. On the 10% slope was 5.3% and on the 30% was 7.4% of the water applied, which was 50 mm. The soil used in the experiments was air dried, and needs more than 50 mm



100 mm/hr

slope = 30%



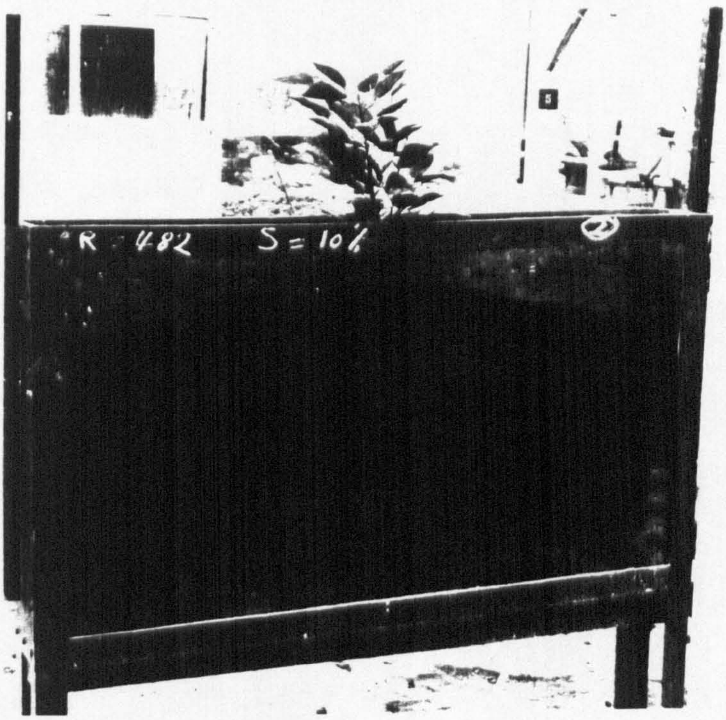
482 mm/hr

slope = 30%

Plate 7.3 Water patterns 24 hours after irrigation for different application rates and 10% slope.

100 mm/hr

slope = 10%



482 mm/hr

slope = 10%

Plate 7.4 Water patterns 24 hours after irrigation for different application rates and 10% slope.

of water to produce runoff with all application rates. This runoff produced may be considered unimportant from an irrigation point of view.

The water penetration into the ridge soil with sideslopes of 10% and 30% was measured 24 hours after irrigation as shown in figure 7.7.

The results of the experiments, as shown in figure 7.7 indicate that most irrigation water (24 hours afterwards) was concentrated either in the centre of the ridge or below the furrow. The effect on water distribution of increasing soil slope is to increase the depth of water penetration below the furrow and, less below the ridge sides, especially with high application rates. The water penetration with low application rate (100 mm/hr) is more uniform than with high application rates.

The results, also show that the water was also concentrated under the plant stem, as a result of stemflow. Also, the interception of irrigation by the crop canopy resulted in less water reaching the soil surface at some spots beneath the plant. However leaf drip added large quantities of water to the soil surface at some spots at the outer edge of the canopy below the top of the ridge. The stemflow measurements varied from 18 to 35% of the irrigation falling on the canopy and, the stemflow was decreasing with the increase in irrigation intensity.

To examine these water patterns with different application rates at different soil slopes, the average depth of water penetration along the ridge profile for for each treatment was determined (table 7.4) by dividing the soil water resvoir

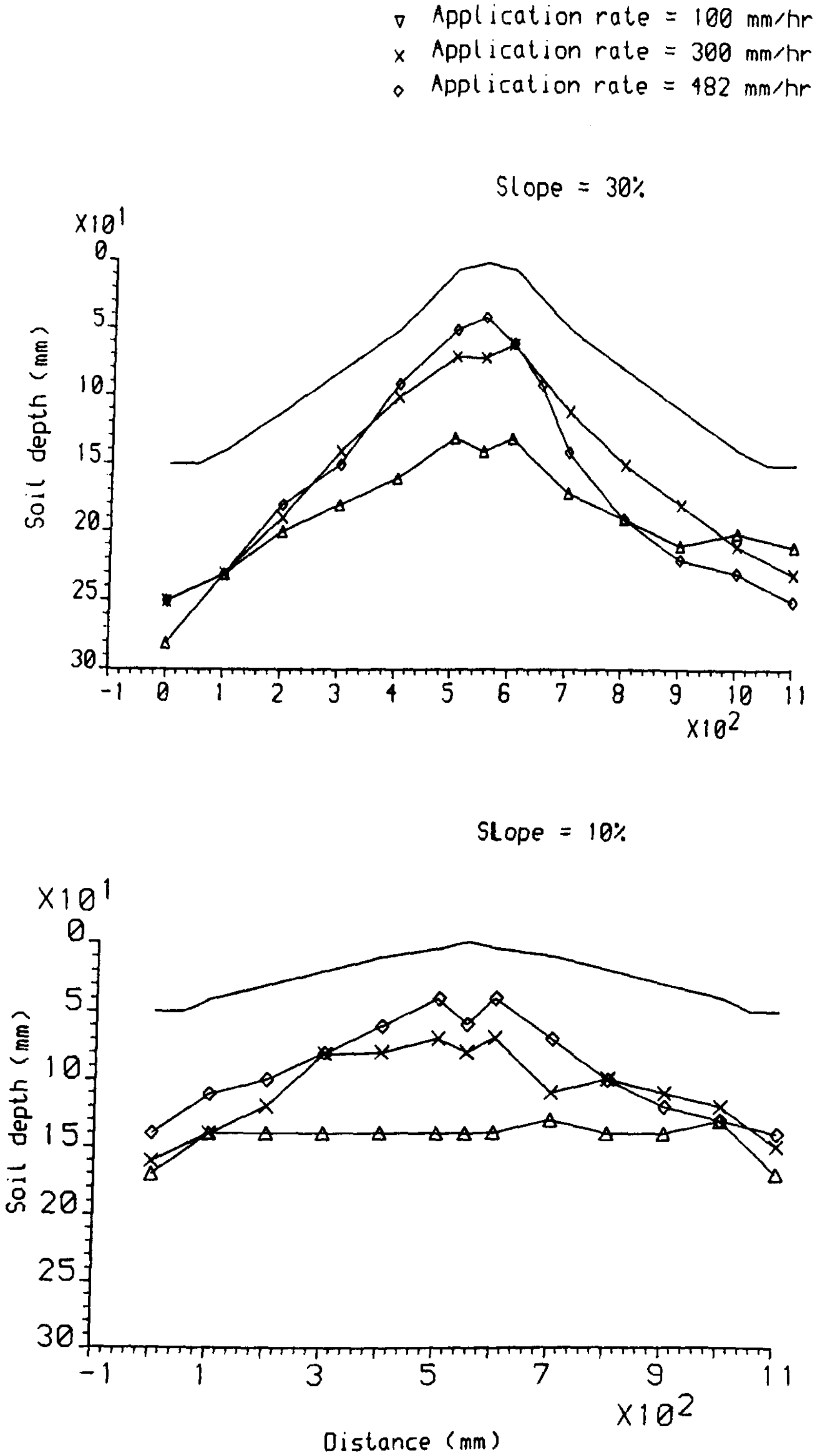


Figure 7.7 Soil water distribution pattern 24 hours after irrigation.

of the ridge into a number of depths measurements, whose upper surface is the soil surface and whose base is the lower boundary of the soil moisture reservoir. It was found that the higher average depth was recorded with the 100 mm/hr application rate at slope 10%, and the average depth for the other treatments was decreasing with the increase of application rate and slope.

Also the water patterns was examined by using Christiansen coefficient of uniformity. Uniformity usually quoted for sprinkler systems are those which are calculated from the distribution of water as it is applied to the soil surface (Hart 1972). The plant, however, responds to the distribution of the water as it occurs within the soil. The coefficient uniformity for the water distribution in the ridge profile in the soil tank soil was determined by dividing the the soil water resvoir of the ridge into a number of depths measurements. The average depth of 100 mm/hr with slope 10% was taken as an average depth in the calculation to compare all the treatments with highest depth. It was found that values of uniformity (table 7.4) ranged from 99% to 58%, and the water distribution was more uniformity with the lowest application rate.

appli. rate (mm/hr)	average depth (mm)		Coeff. uniformity	
	10%	30%	10%	30%
100.0	111.1	107.8	99	97
300.0	83.0	73.4	75	66
482.0	68.0	64.0	61	58

Table 7.4 Values of average depth and coefficient uniformity for the soil water distribution into the ridge profile.

In general, the ridge shape and the plant may influence soil water infiltration for successful use of low pressure spray system. Increasing soil slope and application rate can limit soil water availability because of an uneven soil moisture distribution, and runoff losses into the furrows. The effect of plant canopy on water distribution into the soil profile will depend on the growth stage and plant population.

Also from the water distribution patterns, it can be seen that the ridge profile shape can play a major role in the water availability to the crop. So, soil management practices can clearly change the soil water distribution by changing the shape and size of the ridge profile.

CHAPTER 8
FIELD EVALUATION

8.1 INTRODUCTION

To further develop an understanding of the behaviour of cultivation practices under sprinkler irrigation a field trial was established to measure runoff from a potato crop grown on a ridge and furrow system. As cultivation practice appears to play an important role in making water available to a crop it was decided to examine two further treatments in the trial, namely a tied ridge system and a bed system. Both are suited to the potato crop and there is already evidence from Prestt (1983) to show that the latter is very useful in improving the efficiency of water use not only from irrigation but from also rainfall.

In order to develop similar conditions in the field to those used in the laboratory validation, low pressure fixed spray nozzles were used on a boom system at three application rates, namely 100, 300, and 500 mm/hr. It should be noted that soil used in the validation experiment was taken from the site used for the field trial.

8.2 NOZZLE TYPE AND PERFORMANCE

To apply the water with uniform distribution above the crop canopy with good jet breakup fixed spray nozzles were chosen with different diameters as shown in table 8.1. These nozzles produce small droplet sizes, and good water distribution (Deacon 1981).

nozzle code no.	orifice diam. (mm)	capacity at 83 Kpa (l/s)
7	2.77	0.110
12	4.78	0.232
16	6.35	0.420

Table 8.1 Senninger spray nozzles specification.

The application rates chosen were 100, 300, and 500 mm/hr which are in line with tests carried out for the model validation.

The Farrow Dolphin tow / 60 h boom irrigating machine was use in the field trials. It is a three wheeled, self propelled irrigator designed for horticultural use (figure 8.1). The machine has a single steering wheel at the front, with adjustable width rear wheels for alignment to standard crop rows. Forward motion is achieved with a cable winch mechanism on the machine, powered by a water motor. Water is supplied through a 50 mm flexible hose, which is dragged behind the machine and attached to the main riser by a pull coupling. Two flexible 25 mm hoses are attached to the couplings on the riser, and these supply the water to the spray nozzles attached to the 15.2 metre tubular steel boom on either side of the main frame.

The operating pressure in the field was kept at 83 Kpa (12 ib/in2) for the spray nozzles, by using a preset pressure regulators before each nozzle (figure 8.2). The pressure regulator used was the Senninger pr-12 LF model. The pressure regulator works successfully from a mains of 69 to 416 kpa, Addink et al (1980). Nozzles to be tested were attached to the

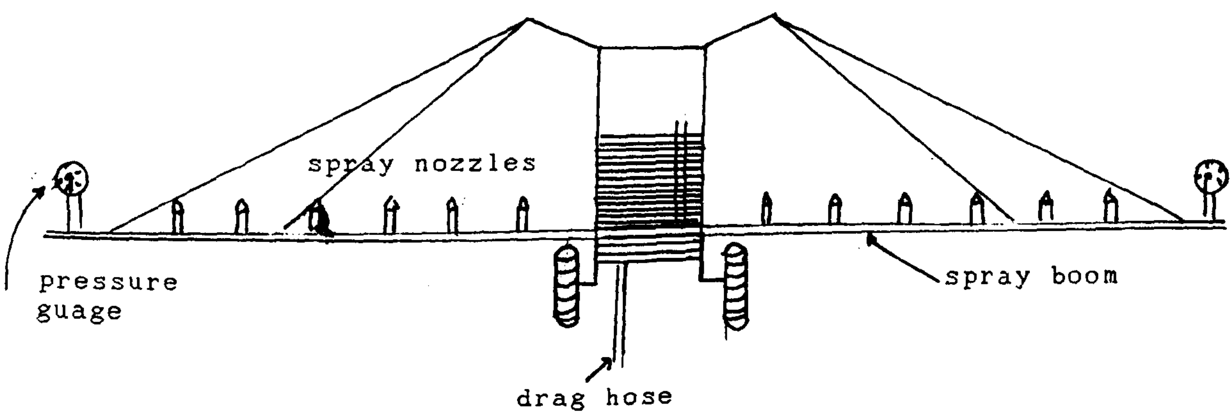


Figure 8.1 A diagram representation of the irrigation machine with fixed spray nozzles.

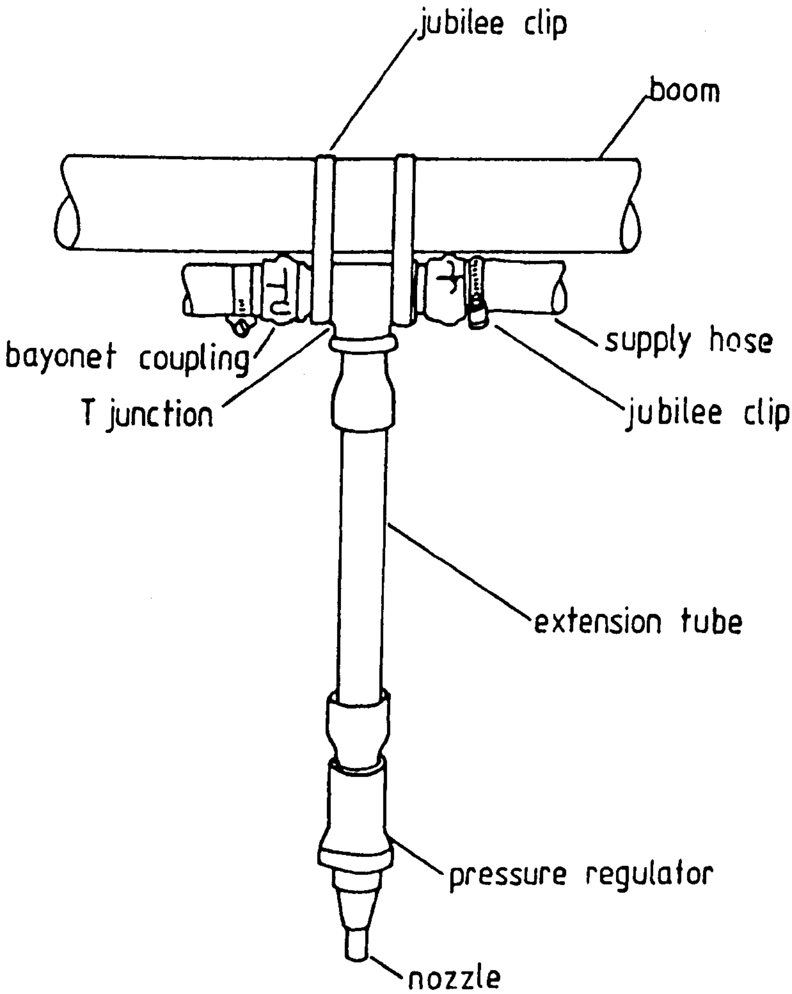


Figure 8.2 Spray nozzle and pressure regulator connected to the supply line through drop tube.

side of the machine mounted sprayer boom with a pressure gauge so that the actual operating pressure could be measured.

The application rate was measured by setting catch cans on a regularly space pattern over the area irrigated measuring the depth of water caught and the time of application at each can for one irrigation. The mean application rate for each point in the pattern was then calculated by dividing the depth of water caught by the time of application.

The water distribution pattern for each nozzle size is shown in figure 8.3. It was determined by placing a line of cans at spacing of 100 mm. Then the cans were exposed to irrigation for a period of 10 minutes. These patterns show that the peak application rate occurs near the nozzle, and decreases towards the edge of the wetted area of each individual nozzle. This concentration of water increased as the application rate increased. These data were used to determine the spacing between the nozzles on the boom.

6 senninger spray nozzles were mounted on the boom attached to the irrigator. The spray nozzles and the irrigation machine can be seen in plate 8.1. Water was supplied by a pump positioned at the river flit, and supplied to the irrigated run in a 75 mm (3 inch) diameter aluminium pipe, from this the 50 mm flexible hose carried the water down the central travel lane, and around a loop lifter before coupling to the irrigator.

The actual spacings between the nozzles on the boom were determined by operating the machine at the required speed, pressure, and adjusting the spacing, and the height of the nozzles from the soil surfaces until 25 mm of water depth was

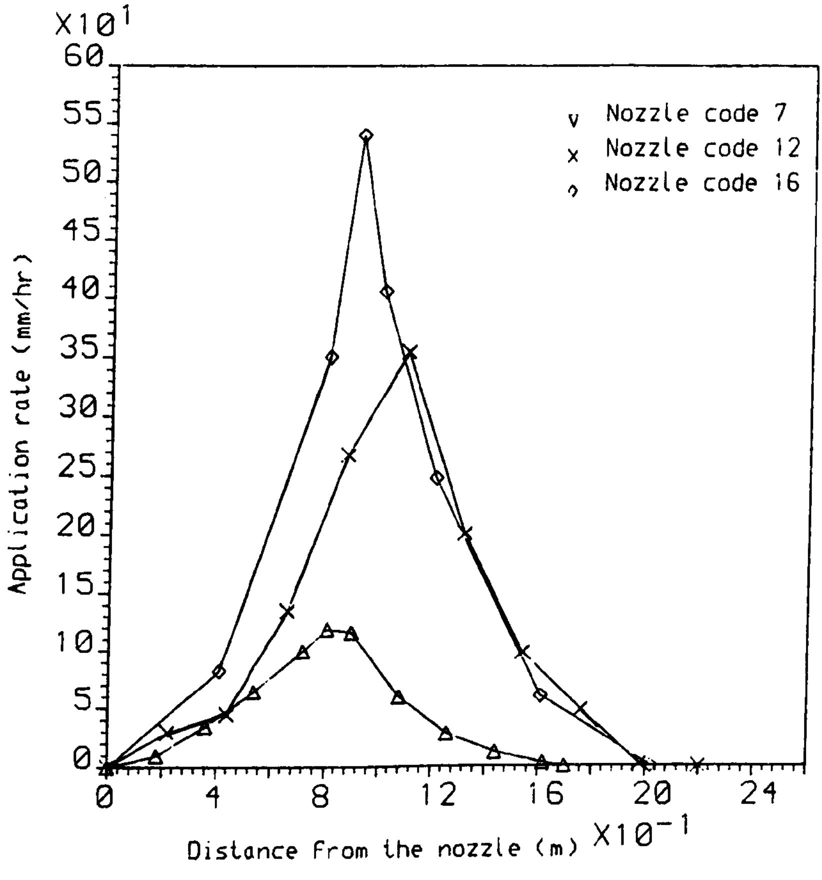


Figure 8.3 Water distribution patterns from three fixed spray nozzles.

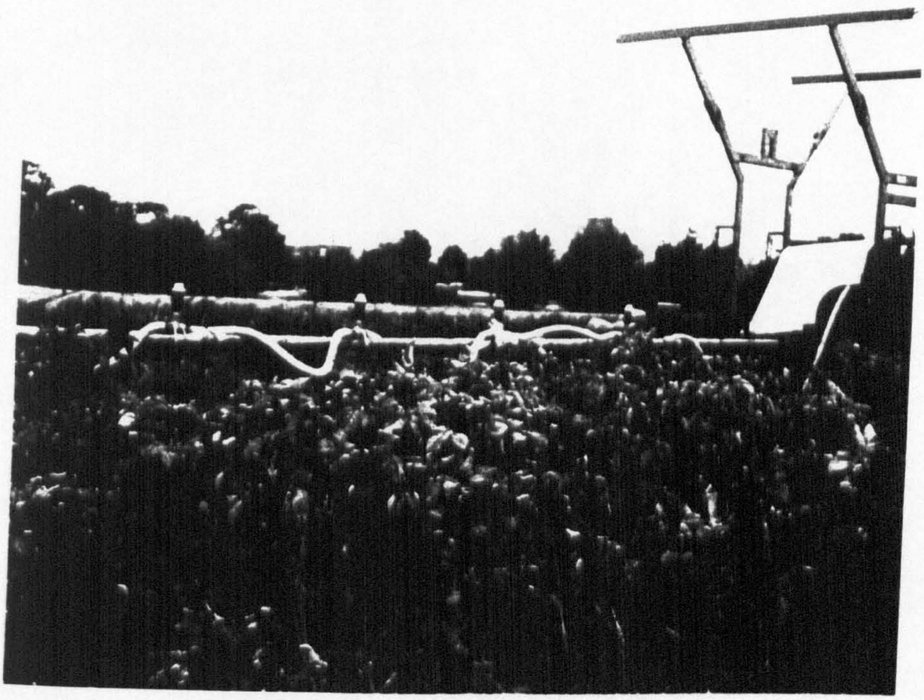


Plate 8.1 Irrigation machine with the fixed spray nozzles.

applied at each pass. The final spacing between each nozzles was 1.2 m, and the height was 1.1 m from the ridge tops.

The travel velocity for an application of 25 mm of water for the three application rates used with the low pressure irrigator and three nozzle sizes were determined (table 8.2).

nozzle code	application rate (mm/hr)	travel velocity (m/min)
senninger 7	100	0.21
senninger 12	300	0.44
senninger 16	500	0.81

Table 8.2 Travel velocity of the irrigation machine for three application rates.

The uniformity of water application was then determined for each set of nozzle sizes, by passing the irrigation machine on a line of cans at spacing of 100 mm in a line at right angles to the direction of travel along the boom. Christiansen's coefficient of uniformity (CU) was used to measure the uniformity of application for each set of nozzles. The cu values are listed in table 8.3.

nozzle code No.	appli. rate (mm/hr)	coeff.uniformity (%)	spacing (m)
senninger 7	100	87	1.2
senninger 12	300	87	1.2
senninger 16	500	86	1.2

Table 8.3 Cu values of three spray nozzle sizes used for the field evaluation.

The evaluation generally showed good uniformity at low pressure of 83 kpa with all spray nozzles.

Measurements of droplet sizes from these spray nozzles have already been made by Deacon (1981) at Silsoe college. The nozzles produced a drop size distribution containing smaller droplet sizes over a range of pressures according to tests conducted by Deacon (1981), as shown in figure 8.4

8.3 SITE AND LAYOUT OF EXPERIMENT

The experiments were carried out at Silsoe Çollege farm, Flitton (figure 8.5). An area of about 0.25 hectare, was used close to the river Flit. The soil type was clay and the mechanical analysis can be seen in section 5.5. There was a water table present on the site during the experiment period with mean depth of about 0.85 m below ground level, although some minor fluctuations were recorded during the trial season.

The field layout was designed to enable the irrigation machine to be used to apply water at different application rates. The field site (figure 8.5) was divided into two sections of cultivation practices, ridges and raised beds, with a break left between the two sections to eliminate any drift of water from the effects of wind and to allow for the machine to travel between them. Each section was divided to a number of plots, each plot was 6 metres in length, and 8 metres in width, and contained 8 crop rows for the ridges, and 6 crop rows for the raised beds, an area sufficient for the field measurements. A break was left between the plots to eliminate any drift of water between the plots, and to allow access for measurements to be

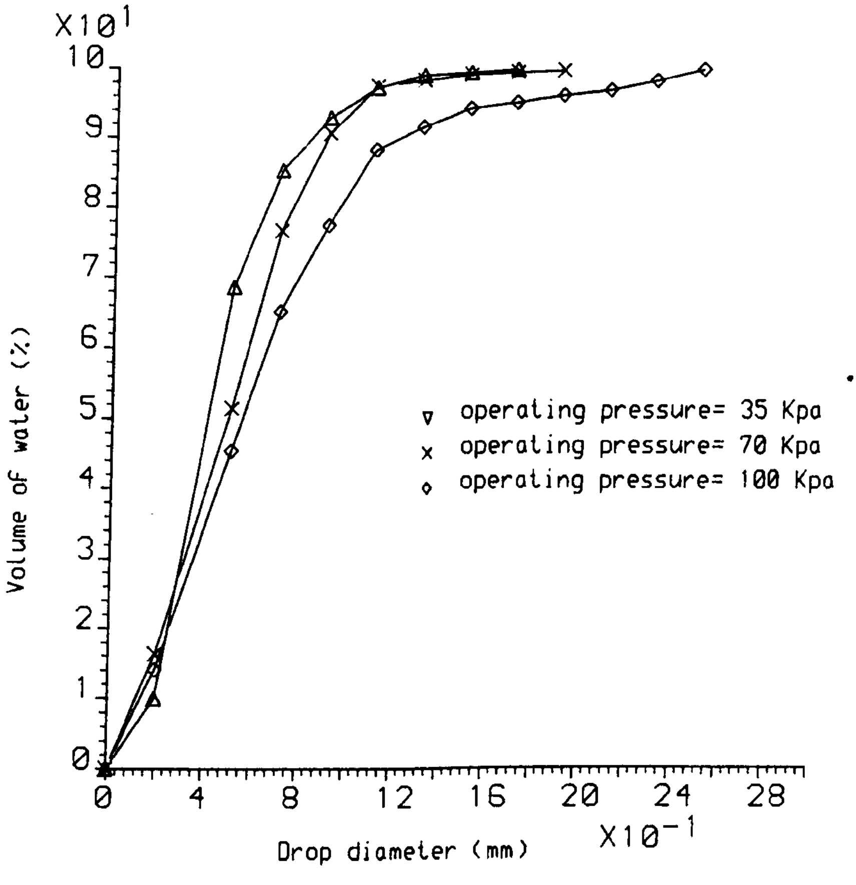


Figure 8.4 Cumulative drop size distribution from a fixed spray nozzle (Senninger code 12) at different operating pressures (after Deacon 1981).

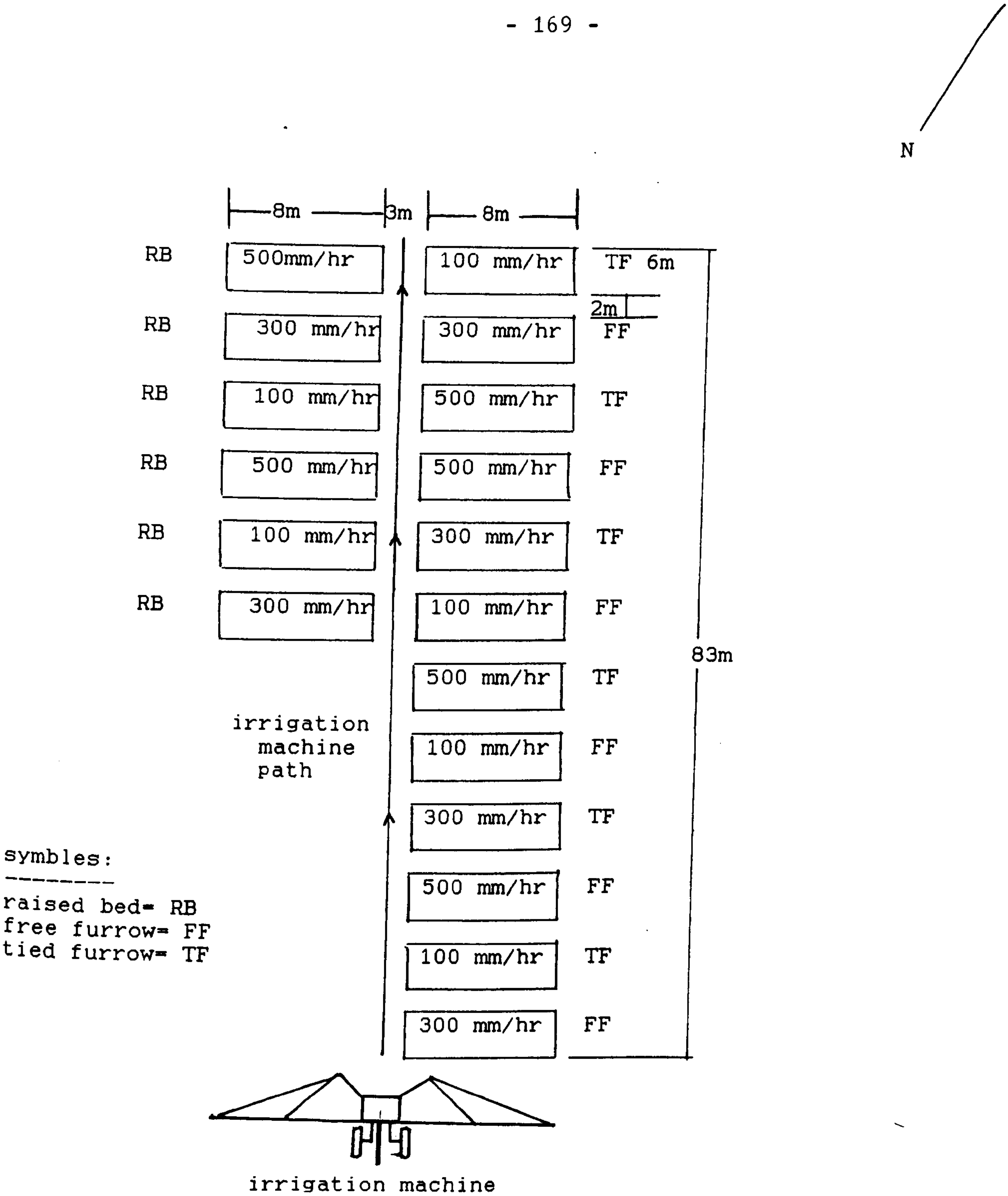


Figure 8.5 experiment layout at the field site.

taken, and nozzles to be changed. A total of 18 plots were required.

The cultivation practices were raised bed (RB), free ridge and furrow (FR), and tied furrow (TF). The tied furrows were created by making small earth banks across the furrow at regular intervals of 3 metres. The soil banks (dikes) were made by hand, because a tied furrow implement was not available.

The crop used was King Edward potatoes. The irrigation machine was used to apply water to 18 plots in total, at three different application rates. Plots at each section were set out in a randomised block fashion, to reduce the effect of any variation in soil characteristics over the field site. Each application rate was used to irrigate 6 plots.

8.4 FIELD MEASUREMENTS

The field measurements were carried out at the field site to determine the water distribution in the soil, and to assess the effect of different application rates on soil structure, and factors resulting from it. These field measurements were

Infiltration Rate

Infiltration tests often reveal soil structural alterations as the rate of water movement is sensitive to changes in pore size. The infiltration rate tests were carried out at field site during the season. Measurements were made using double ring infiltrometers before first irrigation, and after the last irrigation for the two cultivation practices. The cylinders were driven into the soil to a depth of 5 cm, taking care to keep the cylinder sides vertical and avoiding any disturbance of the soil within the cylinders. A measured quantity of water was added, and the water head of 70 mm above the soil surface was kept constant in both cylinders during the tests. A thin piece of wood was placed in the ground, and its top was used as reference head in the inner ring. The experiment was continued until the infiltration rate became constant.

Surface Runoff

Runoff was collected after each irrigation from the free furrow plots and measurements were made using runoff trough into the furrow on the down slope end of the plots, as shown in figure 8.6.

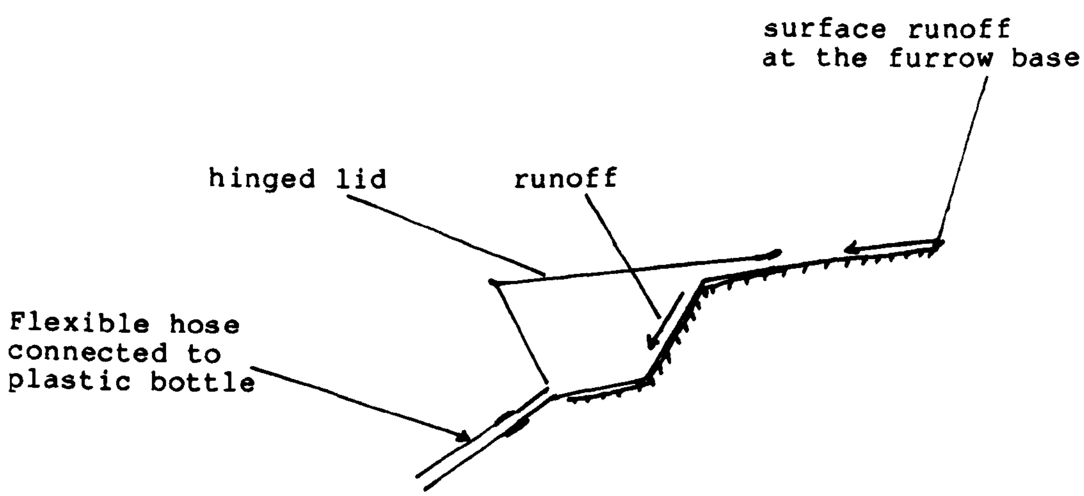


Figure 8.6 Runoff trough to collect surface runoff from the furrow.

A pit was dug behind the trough to contain a 10 litre plastic storage bottle, connected to the trough by plastic hose. The trough itself was equipped with an angle hinged lid, which prevented water from the nozzles falling directly into the trough. Only water flowing in the furrow was therefore collected, and passed to the plastic bottle from which it could be measured.

Ridge Profile

A soil profile meter (plate 8.2) was used to monitor changes in the shape and size of ridges during the season. The ridge profiles were measured before the first irrigation, and after each irrigation, to assess any physical breakdown of the ridge. The device consistsof a frame holding a row of pins with same length, and arranged so that they can move freely and vertically, by a locking mechanism. Successive ridge profile measurements were taken from the same section of ridge. Allowing direct comparison to be made after each irrigation.

Soil Water Content

The soil water content measurements were made before the irrigation started, and after the irrigation, to assess the water movement and changes in soil water content in the crop root zone, for the three cultivation practices. Volumetric soil moisture samples (Reynolds 1970a,b,c) were taken before and after each irrigation. Samples were augured at 100 mm intervals from the top of the ridge and bed to 400 mm below the soil surface. The samples were obtained on a grid basis from a section cut across each cultivation treatment as shown in figure 8.7 for ridge, and for raised bed, respectively.

The neutron probe was used to detect soil water changes at depth up to 0.6 m to reflect the long term water movement beneath

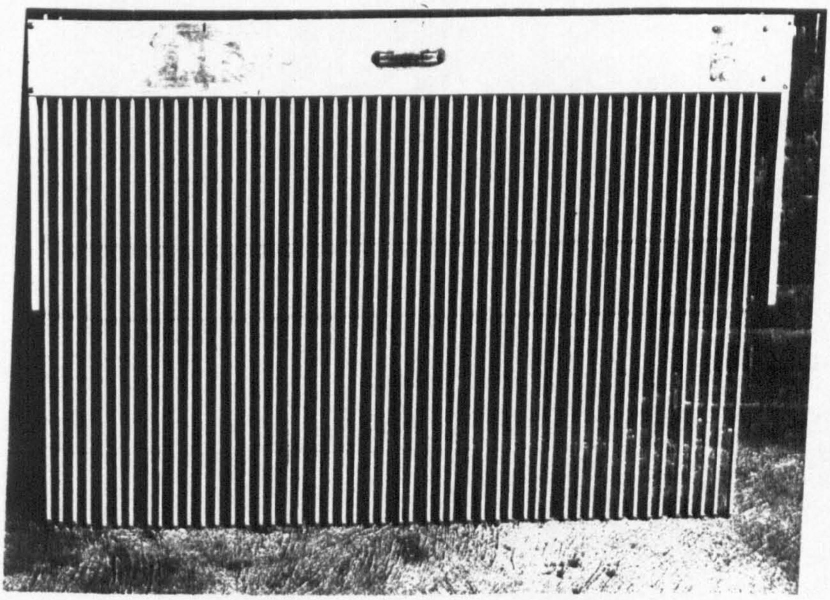


Plate 8.2 Ridge profile meter.

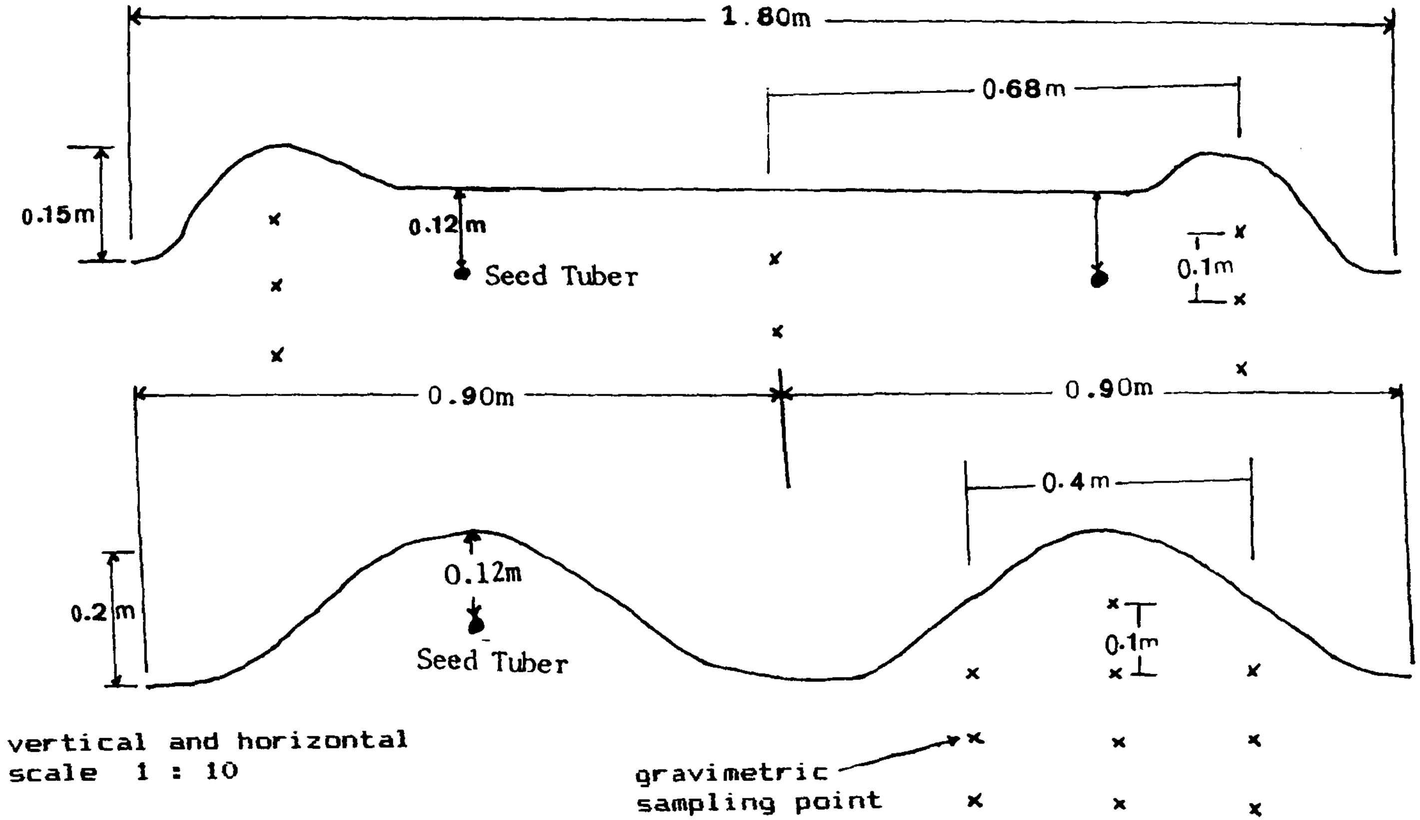


Figure 8.7 Location of gravimetric sampling points in ridge and bed plots.

the cultivation treatments. The location of access tubes was determined to monitor as many as possible within the limit of time available. 27 access tubes of 1 metre length were installed on a grid basis, across each cultivation treatment representing 3 access tubes for each application rate, as shown in figure 8.8 for ridge, and raised bed respectively. Soil water content readings were taken at 100 mm depth interval from the soil surface to 0.6 m below the soil surface. Readings were taken before and after every irrigation, the count ratio was determined by lowering the probe into a tube surrounded by water before each set of field readings were taken to indicate an upper limit to the standard water reading (Rw). Field readings for the day (R) were then divided by this maximum count to give a count ratio (R/Rw)(Bell 1976). The relationship between the count ratio and the volumetric water content (θv) can be described by the following linear equation:

$$\theta v = 0.68\ (R/Rw) + 0.08 \quad . \quad . \quad . \quad . \quad . \quad (8.1)$$

Due to the inaccuracy with which the neutron probe measures soil water content in the top 300 mm of the soil profile, as a result of the soil/air interface (Grant 1975) this particularly relevant in ridges where the shape of the ridge can cause a considerable loss of neutrons through the soil/air interface (French and Legg 1973). Also, Vauclin et al (1984) showed that by soil water content measurements within neutron probe the location error is often more important than instrument or calibration error. This set-back in the neutron probe measurement made the use of it limited especially at the top 300 mm of the soil root zone.

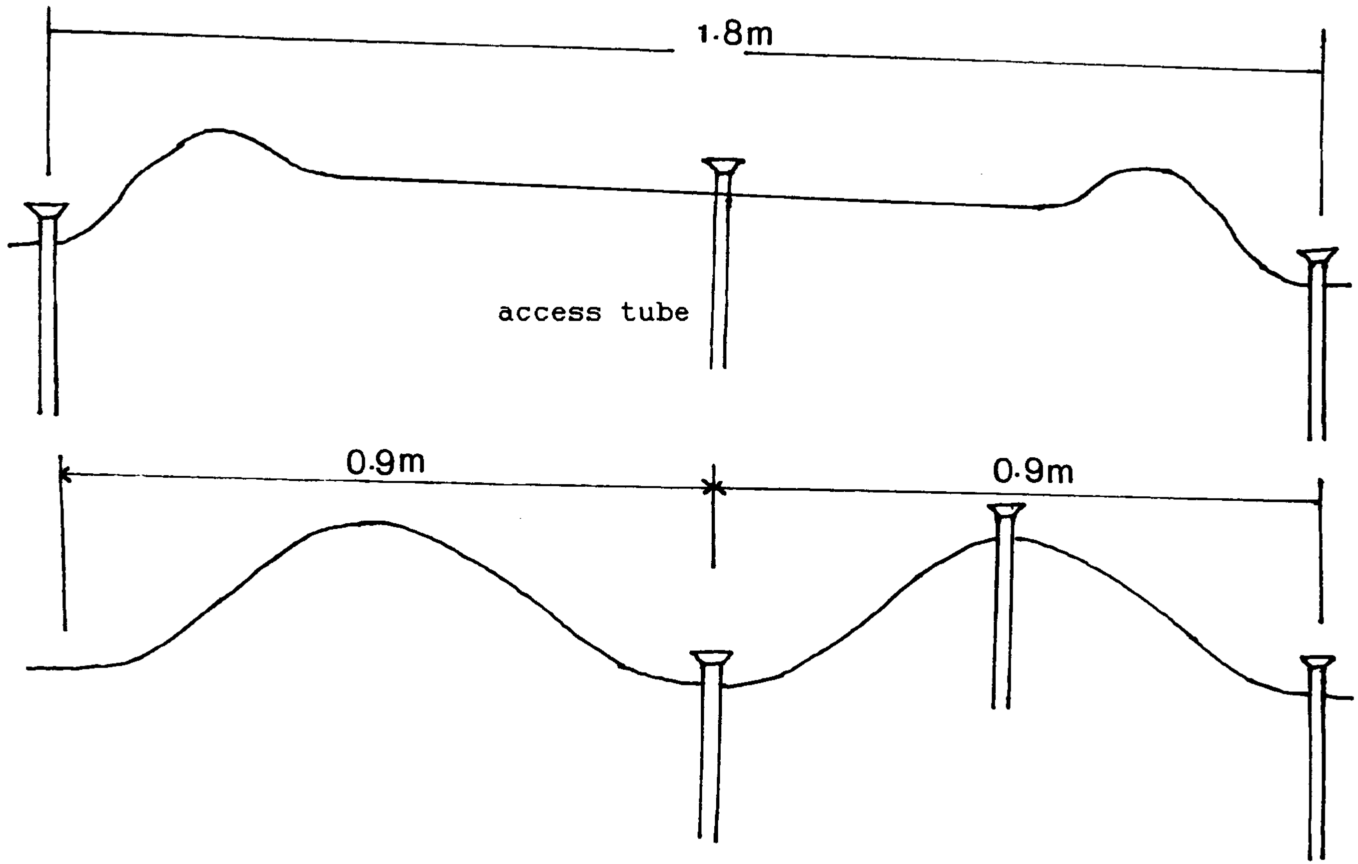


Figure 8.8 Location of Neutron probe access tube in ridge and bed plots.

8.5 IRRIGATION SCHEDULING

An important aspect irrigation is to determine how much water to apply and when to apply this water to the crop. For calculating the latter, a suitable soil water deficit level should be set for the particular crop. Singh (1969), and Harris (1978) have shown that the soil water deficit in a potato crop should never fall below 50% of the available water capacity in the crop root zone. Salter and Goode (1967) stated that for the King Edward variety irrigation should be done before the soil water deficit exceeds 25 mm regardless of soil type (in the top 300 mm of the soil).

In this experiment it was decided to irrigate when the soil water deficit reached 25 mm in the crop root zone. This level of soil water deficit was selected on Salter and Goode recommendations (1967) for the King Edward variety and because the soil could be brought to field capacity with 25 mm irrigation application amount.

There are various methods of calculating the water status of the soil on which to base decisions concerning when to irrigate and how much water to apply.

During the trial period, four irrigations, each 25 mm of water were scheduled according to when the soil water deficit reached 25 mm in the crop root zone. The irrigation scheduling was done using the computer scheduling program available at Silsoe College. The program estimates actual rate of water use for a crop and estimates the current soil water deficit. It then predicts the date of next irrigation, and the amount of water to apply. The soil water balance sheet for the season is shown in the appendix A.4. Rainfall was recorded from a rain gauge at the field site. From the balance sheet, it is evident that a significant amount of rainfall fell during the cropping season, and so soil water distribution results were likely to be significantly affected by the rainfall and not just irrigation. When the applied irrigation or rainfall was in excess of the soil water deficit, it was assumed that this additional water was lost to drainage. Some time the soil water deficit of 25 mm was exceeded before irrigation namely first and third irrigation, and that was due to problems with the equipment.

8.6 RESULTS AND DISCUSSIONS

Before considering the results of the experiment in detail, it is useful to describe the weather conditions on the site during the experiment. The season was wetter than average and this clearly affected the results. The average monthly increase in rainfall during the season was 2% comparing to the last 33 years from 1951-1984. (the average monthly of the season was 55.6 mm where as the last 33 years was 49.1 mm).

The effects of the water application rates on the physical properties of the soil are presented and discussed, including their influence on water penetration into ridges and beds. The effects of these treatments on soil infiltration, soil erosion, surface runoff, and soil water distribution in the soil crop root zone are also presented and discussed.

8.6.1 Soil Infiltration Rate

The results obtained from the infiltration tests are shown in figures 8.9 to 8.10. A number of infiltration tests were conducted on the soil before first irrigation started are shown in Figure 8.9 on furrow plots and the raised bed plots. These infiltration tests were repeated at the last irrigation (fourth irrigation) of the season for the two of the cultivation treatments to assess and compare the effect of each application rate on infiltration rate, these are shown in figure 8.10

The results show that the infiltration rate for the raised bed plots is much higher than that for the furrow plots at the beginning of irrigation and after the fourth irrigation. There is a reduction in infiltration rate between the first irrigation and fourth irrigation on both cultivation treatments. The reduction in infiltration rate is greater when the the application rate is greater despite the same amount of water being applied. The trend of decreasing infiltration rate is similar for all the plots, but the reduction is more significant at the higher application rates. The decrease in infiltration rates was due to the formation of surface seal resulting from the breakdown and destruction of the aggregates resulted in plugging of the macropores by washed material as stated by many workers, including McIntyre (1958), Hanks and Bowers (1963), and Moldenhauer and Long (1964). The aggregate breakdown increases with the increasing of water application rate, this reduction can be seen in figure 8.10, where the infiltration rate decreases with the increase of application rate. This because the low application rates consistently produced a weaker crust(Busch et al 1973).

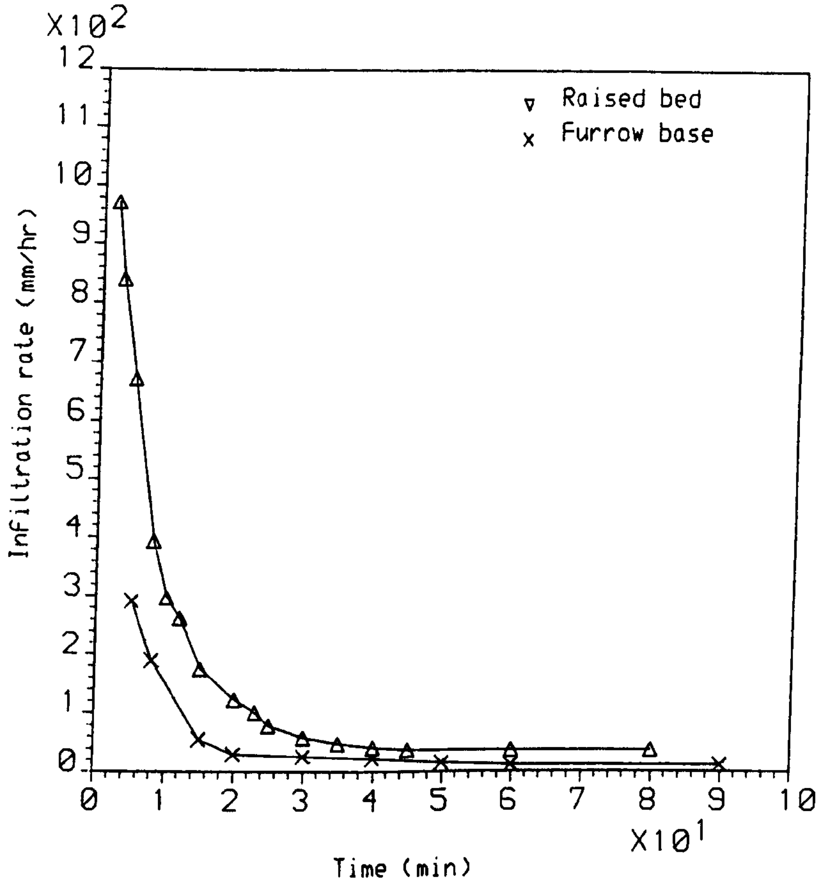


Figure 8.9 Infiltration rates on furrow base and raised bed plots before first irrigation.

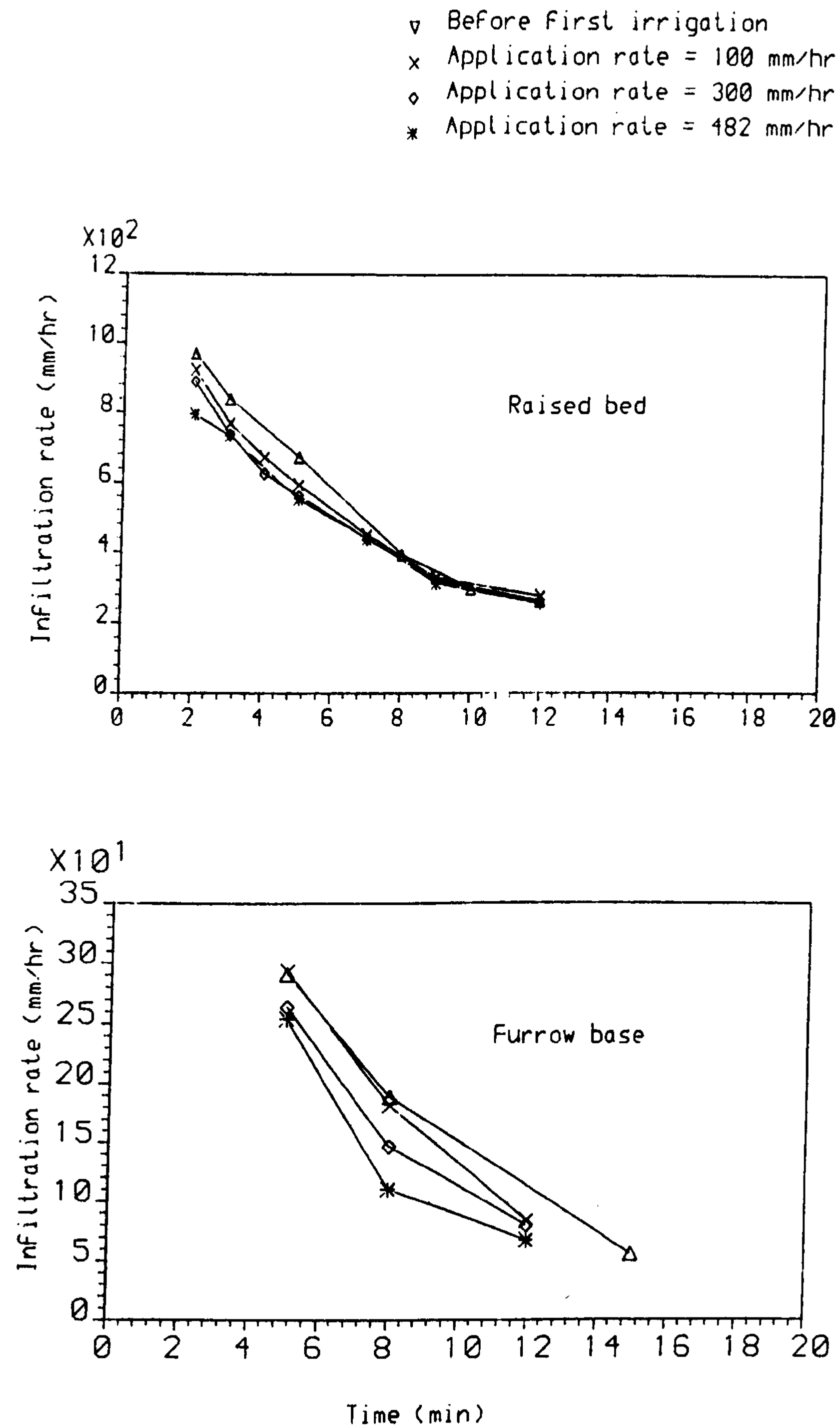


Figure 8.10 Infiltration rates on furrow base and raised bed plots before first irrigation and after fourth irrigation for three application rate plots.

There is a difference between the final infiltration rate for the ridges and raised beds treatments. In the raised bed plots less surface sealing and compaction were visible and the soil surface generally was more friable than that of the furrow, a portion of the difference may have been due to less compaction from wheel traffic during ridge formation.

These results show that there was a reduction in soil infiltration rate in both cultivation practices under the three application rates, but the reduction was not very large even with high application rate. The small reduction may be related to two factors. The first factor was the cushioning effect of the crop canopy that dissipated some of the impact forces of the water drops and maintained higher infiltration rates, in fact the crop cover at first irrigation was about 77% of full cover. The second factor was the creation of a thin surface of film water during the water application (Gilley and Finkner 1984). This film of water on the soil surface offers a protection to the structure of the soil from the impact of raindrops. With the high application rates a film of water occurred over a very short period of time. The reduction in infiltration rate was also affected by the rainfall which occurred between the first and fourth irrigation.

8.6.2 Surface Runoff

Runoff measurements are presented in table 8.4. The volume of surface runoff collected in each runoff trough was converted to a depth (mm) by dividing it by the furrow area (i.e. the length of the furrow 6 m multiplied by the width of the

Irrigation No.	Cultivation treatment	appl. rate (mm/hr)	measured ruoff (mm)
1	raised bed	100,300,500	0.0
	tied furrow	100,300,500	0.0
	free furrow	100,300,500	0.0
2	raised bed	100,300,500	0.0
	tied furrow	100,300,500	0.0
	free furrow	100	0.0
		300	0.03
		500	0.08
3	raised bed	100,300,500	0.0
	tied furoow	100,300,500	0.0
	free furrow	100	0.0
		300	0.014
		500	0.044
4	raised bed	100,300,500	0.0
	tied furrow	100,300,500	0.0
	free furrow	100,300,500	0.0
Potential runoff (mm)	free furrow	100	0.0
		300	0.6
		500	6.3
Predicted runoff (mm)	free furrow	100	3.59
		300	5.85
		500	7.41

Table 8.4 Measured, potential and predicted runoff / plot from the field site.

furrow-ridge 0.9 m). No runoff occurred from the raised bed plots or tied furrow plots for all the three application rates, and there was no runoff resulting from rainfall.

From the results obtained, the runoff occurred at the higher application rates of 300 mm/hr and 500 mm/hr, but there was no runoff at 100 mm/hr from the free furrow plots. No runoff occurred from the raised bed plots and that could be related to the high infiltration rate, and the lack of slope on the plots. The dikes in the tied furrow completely eliminated runoff. Thus it is clear dikes may be a reliable alternative for runoff control, particularly on sloping fields. These dikes held water on the soil longer thus allowing water to infiltrate.

In general the paucity of runoff is due in large part to the lack of the slope of the field plot, and high infiltration rate. The crop also played a major part in preventing runoff running down , because a large number of plants stems and branches lying prostrate in the furrow base, effectively preventing the movement of water along the furrows and kept the runoff on the furrow base. The results show that runoff was not high in this case, and there was no runoff at fourth irrigation.

Comparisons between results of measured runoff at the field site, potential runoff and predicted runoff by the model were made and are shown in table 8.4. The potential runoff calculated under the three application rates from figure 8.11. The results showed variation between these comparisons, and the variation between each result is related to the way it was measured or calculated. The calculation of potential runoff is based on calculating the difference between application rate and

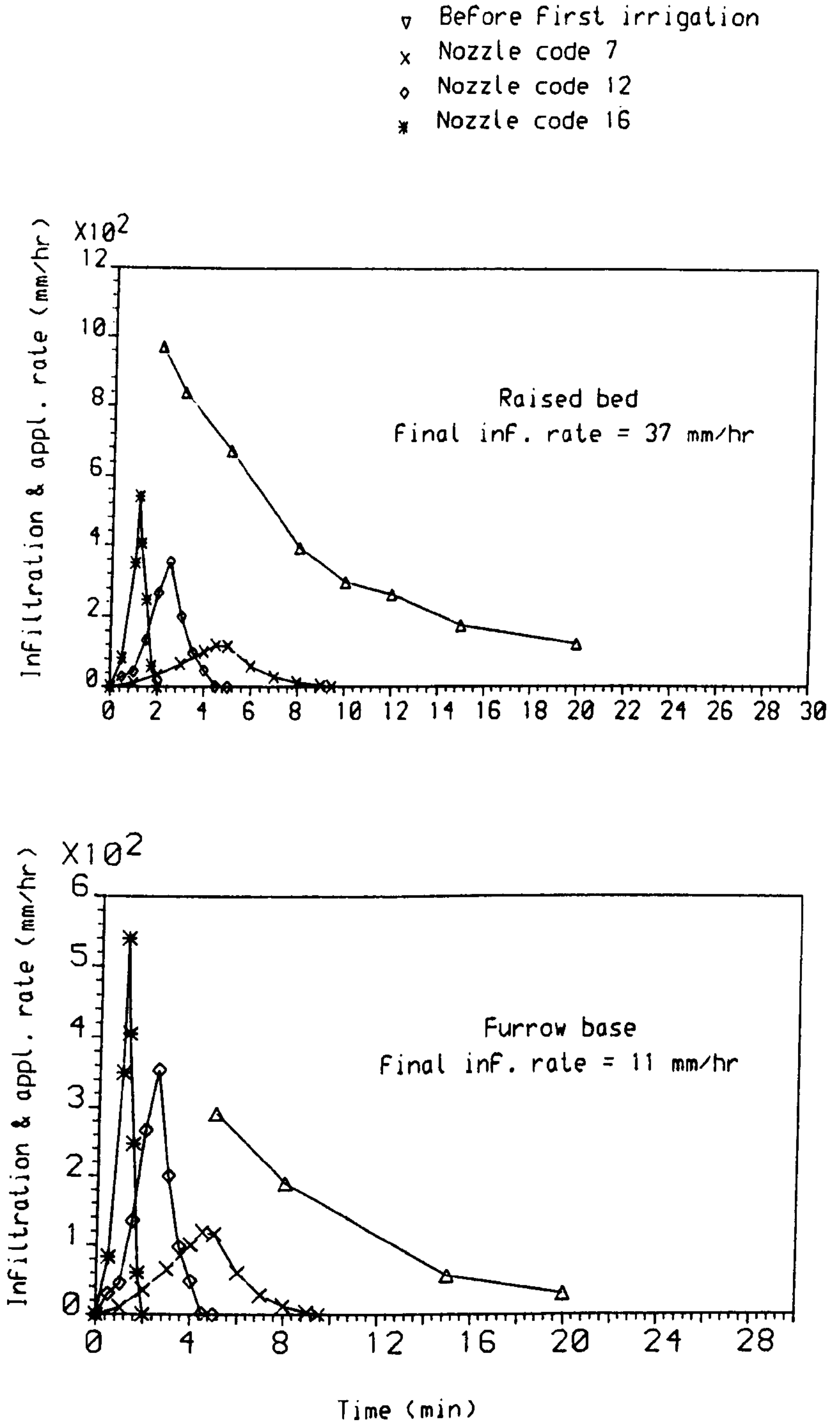


Figure 8.11 Infiltration rates before first irrigation for furrow base and raised bed plots and application rate patterns of three nozzles.

infiltration into the soil, neglecting surface depression storage and interception loss. The surface depression storage is affected by the three main topographical components which affect the amount of runoff, namely the slope of the field, the depth and direction of the furrow and the roughness of the field. These components affect the amount of actual runoff which the potential runoff ignored. Also, the runoff was predicted by the model and the prediction is greater than the measured and the potential runoff. This is because the model predicted the runoff from the ridge sideslopes only taking into consideration the slope steepness and the interception loss, but did not take into consideration the depression storage on the furrow base and its slope steepness. The depression storage could be varied as reported by many workers, Gayle and Skaggs (1978). They reported that depression storage values for clay loam and sandy loam ranged from 8 mm to less than 1 mm, and Larson (1979) found that for swelling clay soils it can approach 25 mm of water when the soil is cracked.

8.6.3 Ridge Profile Detachment

The actual changes in ridge cross-sectional area over the season are given in table 8.5.

Appli. rate (mm/hr)	A1 (m2)	A2 (m2)	% reduction in ridge c.s.a
100	0.1331	0.1281	3.82
300	0.1332	0.1235	7.25
500	0.1291	0.1178	8.81

A1 = ridge area before first irrigation
A2 = ridge area after fourth irrigation

Table 8.5 Reduction in ridge cross-sectional area (c.s.a.) under different application rates.

In general the reduction in ridge cross sectional-area increased with the higher application rate, but the reduction is small with all application rates. The crop cover may play an important factor in protecting the ridges from interrill erosion during irrigation, because the first irrigation was applied when the crop cover was about 77% of full cover. The results also indicate that high application rate over short period of time results in more soil detachment than lower application rate over longer time period even with the same amount of water applied. But, there was little reduction in the cross-sectional area at the ridge during the season, even with 500 mm/hr application rate, and soil detachment could not be a problem.

8.6.4 Soil Water Distribution

The change in soil water content in the soil profile of each soil cultivation treatment was determined before and after each irrigation using the gravimetric sampling and neutron probe. The soil water distribution patterns and graphs for the gravimetric sampling and neutron probe data for the fourth irrigation are shown in appendix A.3 to represent the measurements collected during the season.

The soil water distribution in the soil profile shows that the water content was higher below the bottom of the furrows than that of the ridges, and this concentration increases with the increase of application rate for all cultivation treatments. This finding is in agreement with that obtained in the laboratory experiments (section 7.7) and by Saffigna (1976) and Prestt (1983). The ridge sideslopes played an important part in causing the water to accumulate at the furrow base as a runoff. Also the water measurements in the soil profile showed that the water content on the tops of the ridges was low, indicating that the crop reduced the water falling directly onto the tops of the ridges. The flow of water down the stems of the plant, and into the tops of the ridges which is common with many crops was not apparent in this case, and this was probably due to the large crop cover at the time of irrigation where the stems no longer grew vertically upward from the base, but tended to bend over into the furrow. Many of the smaller stems, particularly during irrigation were bending over towards the furrow, and thus most of the water directed down the sides of the ridges, and in the furrows. In addition water distribution beneath the bed was more uniform than under ridges as shown in appendix A.3.

The measurements obtained during the season were affected by the amount of rainfall which was sometimes difficult to assess the effectiveness of each application rate in the placement of water into each cultivation practice. In fact, the water content below the bottom of the furrow at depth of 300 mm is some time higher than the water content at field capacity (mean field capacity was 53.6 % by volume) even in some plots before irrigation. This probably due to low infiltration rate and the compaction of the soil caused by the tractor wheels at these furrow profile which will keep the irrigation water and rainfall for longer period.

The fourth irrigation measurements were chosen to demonstrate the behaviour of water distribution in the crop root zone for each cultivation practice and application rate. To examine the soil water distribution for each cultivation practice before and after the fourth irrigation on a quantative basis, by converting the individual water contents to a depth of water contained in the soil crop root zone per unit depth of soil (figure 8.12). Using the gravimetric sampling to make a detailed assessment of the water conditions within the root zone for each cultivation treatment before and after fourth irrigation. A total soil root depth of 0.3 m was assumed for every cultivation treatment, and an effective soil root zone width of 1.8 m for the raised bed and 0.9 m for the tied and free furrows. Although the soil crop root zone can not be assumed to be the exact soil crop root zone area for the whole crop, it is likely that the area contains most of the concentration of roots. The amount of water contained in the top 300 mm of soil within the crop root zone was then calculated for each cultivation treatment for fourth irrigation and the results are shown in table 8.6. By comparing the quantity of water contained in the soil crop root zone for each treatment, the effectiveness of each application rate in placing the water in the soil root zone can be assessed. There was a difference between each treatment in the quantity of water was needed to return the soil to field capacity, and the amount of water held in the root zone. This difference could be related to the wet season which had some effect on this and kept the water table at depth Of 0.7-1.0 m from the furrow bed, also the soil variability which exist at the field site.

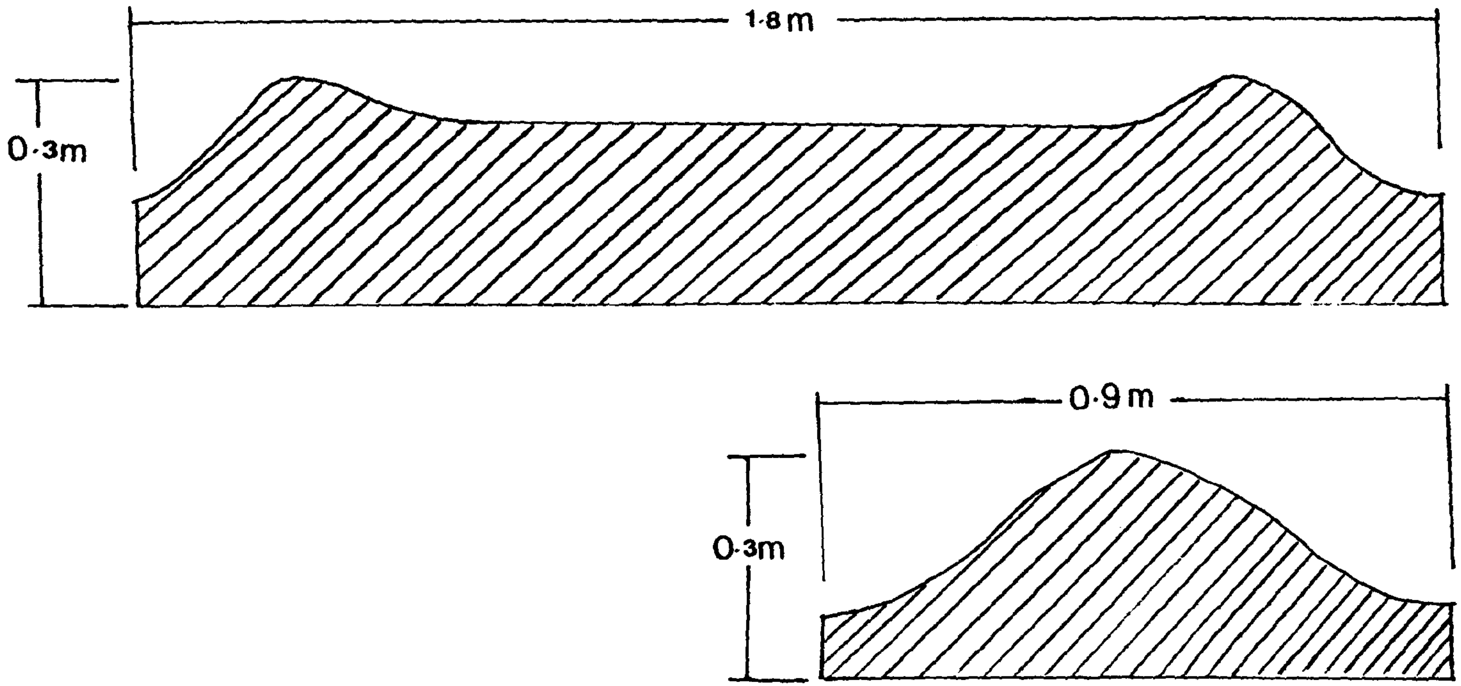


Figure 8.12 Schematic representation of raised bed and ridge cross-sectional area.

application rate (mm/hr)	cultivation practice	SWD (mm)	WS (mm)
100		22.4	17.8
300	tied furrow	21.3	13.3
500		17.2	7.95
100		22.2	9.7
300	free furrow	31.0	18.9
500		20.5	16.6
100		30.0	20.4
300	raised-bed	34.0	17.4
500		24.0	13.2

SWD = Soil water deficit in the soil root zone before fourth irrigation.
WS = Water stored in the soil root zone after fourth irrigation.

Table 8.6 The amount of water stored in the soil root zone before and after fourth irrigation.

The uniformity of water distribution obtained from the two measurements for each application rate and cultivation treatment was investigated by using statistical measure of uniformity. The Hawiian sugar planter's association uniformity coefficient, UCH (Hart 1961, 1972) was used as the distribution parameter. This equation has been used by many workers to determine the uniformity of water distribution in the soil profile, and it has advantages on the Christiansen equation which have the physical interpretation useful in predicting the performance of irrigation system and the equation suits unarrayed data (Hart 1961). The UCH is based on the standard deviation (s) and the mean water content (M) which can be written in the following form :

$$UCH = \left(1 - \sqrt{2/\pi} \cdot s / M \right) 100 \quad \ldots\ldots \quad (8.2)$$

The UCHs were calculated for all the measurements of soil water contents before and after fourth irrigation by gravimetric and neutron methods (table 8.7). It can be seen from the table that the uniformity of water distribution within the crop root zone is more uniform for the raised bed plots for both measurements, and the tied furrow is relatively more uniform than that of free furrow especially with measurements after irrigation. The uniformity variations within one cultivation practice could be affected by one of several factors including rainfall, crop canopy, soil texture, profile development, initial soil water, and experimental error within the measurement method.

appli. rate (mm/hr)	Tied furrow UCH1	UCH2	Free furrow UCH1	UCH2	Raised bed UCH1	UCH2
UCH before irrig.						
100.0	84	91	73	83	86	93
300.0	74	89	87	78	94	89
500.0	75	85	84	91	86	96
UCH after irrig.						
100.0	85	94	81	86	86	95
300.0	82	90	80	91	87	91
500.0	84	91	78	95	89	94

UCH1 = uniformity by gravimetric sampling.
UCH2 = uniformity by neutron probe.

Table 8.7 Uniformity values for water distribution for three application rates.

In general the soil water distribution from the two methods of measurement was non-uniform and the water was concentrated more under the furrows than the ridges. The amount of water stored in the ridges decreased with the increase in application rates. These differences were probably due to the leaf drip which tended to drip the water to the centre of the furrows as the application rates were increased, and the runoff from sides of the ridge. The soil water distribution was more uniform in the raised bed plots than the free furrow and tied furrow plots, and the uniformity for water distribution for tied furrow was higher than the free furrow. Also the water deficit in the raised bed was higher than the others ~~and~~ because the infiltration rate is high in the raised bed treatments.

8.7 CONCLUSION

The results of this field trial confirm the importance of the relationship between water application rate, soil cultivation practice and the crop in controlling the surface runoff and soil water distribution. But due to the rainy weather conditions during the season, comparisons and conclusion were difficult to make for the efficiency of each cultivation practice and application rate in the placement of water in the soil root zone.

The crop canopy played a major role in the results of the soil infiltration rate, soil ridge detachment, and water distribution during irrigation.

The results show that the soil infiltration rate decreased for each treatment, and this reduction was higher with higher application rates, the infiltration rate for the raised bed plots was higher than that for the free furrow and tied furrow plots during the season.

There was no runoff from the raised bed plots for all application rates, and the dikes in the tied furrow completely eliminated runoff. The surface runoff was collected only from free furrow plots, and the runoff was not high and not significant in this experiment. The model prediction was compared to the measured runoff. But more field experiments are needed in this area taking into consideration the depression storage and interception loss at different growth stages of the crop.

Measurements of the ridge profile detachment show minimal damage resulted from the use of low pressure sprinkler irrigation system. The detachment caused by all three application rates was insignificant and not be a problem.

The soil water distribution in the soil root zone was not uniform for all cultivation treatments under the different application rates. The soil water distribution was more even in the raised bed plots and then tied furrow plots comparing to the free furrow plots. There was a difference in the amount of water stored in the soil root zone before and after irrigation for each cultivation practice. The water stored in the ridges was less than the furrow because of drying ridges, an uneven soil water distribution and runoff losses into the furrow. This can limit soil water availability to the crop. Decreasing the ridge sideslope or changing the shape of cultivation treatment may play an important in the water availability to the crops and reduce runoff.

CHAPTER 9

CONCLUSIONS

9.1 MEETING THE OBJECTIVES

The main objective of this study was to begin the development of a mathematical model which would simulate the operation of a sprinkler-soil-crop system as a more effective aid to design.

This objective was met by development of a numerical mathematical model based on the kinematic wave theory which is able to predict runoff (and hence infiltration) from a small agricultural catchment under a wide range of water applications, soil and cultivation conditions. The model incorporates provisions for a variable infiltration rate, a variable application rate, and a variable soil slope.

The model was further developed to include the water intercepted by a crop canopy during irrigation.

Both models were validated by experiments in the laboratory. A field trial was also undertaken but proved less successful in validation because of unfavourable weather conditions.

Based on the results of the study the following summarises the main conclusions.

1- Kinematic wave theory based on the continuity and momentum equations can adequately describe the surface runoff on very short slopes Such as those occurring in ridge and furrow cultivation.

2- The model was able to predict runoff resulting from a wide range of irrigation application rates, different slopes and different soil infiltration rates.

3- Verification of the model was achieved by comparing the numerical results of runoff computed by the model with those obtained by laboratory experiments. The performance of the model was in a good agreement with the experimental results.

4- A model was also developed to assess the amount of water intercepted by the crop canopy during irrigation. This model was also validated in the laboratory using an artificial plant and there was good agreement between the results from the model and the experiment.

5- It is possible to combine the runoff and interception models to provide a more realistic answer to the assessment of runoff under a croping conditions.

6- Increasing the ridge sideslopes can limit soil water availability to the crop because of an uneven infiltration and soil water distribution and excessive runoff losses into the furrow.

7- A limited study of the distribution of soil water following irrigation on a ridge and furrow system was made using a soil tank. This indicated that soil water increases at the bottom of the furrow bed with an increase of application rate.

8- Also a limited field study of the distribution of soil water following irrigation on a range of cultivation practices was made. This indicated that soil water distribution uniformity in the soil root zone was higher for raised bed cultivation than the ridge and furrow cultivations.

9- The results of a field trial suggest that the tied furrow cultivation practice is effective in preventing runoff and as such will increase irrigation efficiency by preventing runoff to low areas.

10- Also the results suggest that the level of soil structural breakdown from ridges was not a problem with all application rates used in the experiments.

11- It was found that the cultivation practice can improve the uniformity of soil water distribution in the soil root zone.

12- The constant Manning's n of 0.018 gave a good results for the small catchment. However, in reality n is not constant but will vary with flow depth (discharge). But sensitivity analysis indicated that a small variations in n value had a minor effect on the runoff value, other factors remaining unchanged.

9.2 SUGGESTIONS FOR FURTHER RESEARCH

There is a need for further research on the development of low pressure irrigation system to reduce the problem of runoff occurrence associated with the system. In general future research should be concerned with conserving water and replacing and retaining it where it is most needed, in the soil root zone. As one of the most important function of the model is to predict the runoff on a simple catchment with or without crop cover under simulated rainfall, the following are some suggestions for further work on the existing model concerning its use for management and design purposes.

1- Whilst the model showed very good agreement with the validation experiments in the laboratory, further research is needed to test the model in the field. Field measurements on a wide variety of agricultural soils need to be made in order to develop a general model for predicting runoff. This would allow for the proposed model to be applied to a wide variety of soils and crop covers and would thus assist in management decisions, particularly in respect to optimum water application rates with different cultivation practices and crops.

2- The infiltration component of surface runoff model need to be tested on field data for a variety of cultivation practices. Initial soil water content should be estimated using daily models that account for drainage and evapotranspiration.

3- Sufficient area of the test surface should be available, so that the depression storage and hydraulic roughness can be evaluated. Also, the effects of raindrop and unevenness of the soil surface have on the hydraulic roughness, and runoff would be useful study.

4- The testing of the interception model in the field with a crop is desirable.

5- In many cases the catchment hydraulics may follow a laminar flow relation for part of the run, and a turbulent flow relation for another. Further laboratory and field studies are needed to establish the type of flow regime experienced on small agricultural catchments.

6- Further research is required on the influence of the shape of cultivation practice on the soil water distribution (horizontal and vertical) within the profile and its availability to the crop.

7- Water applicator devices tested to date have not been fully satisfactory. New devices capable of uniform water application at low pressure over long distance are needed.

8- Bed or ridge shaping equipment to minimize runoff and soil erosion and to increase the wetted crop root zone need to be developed.

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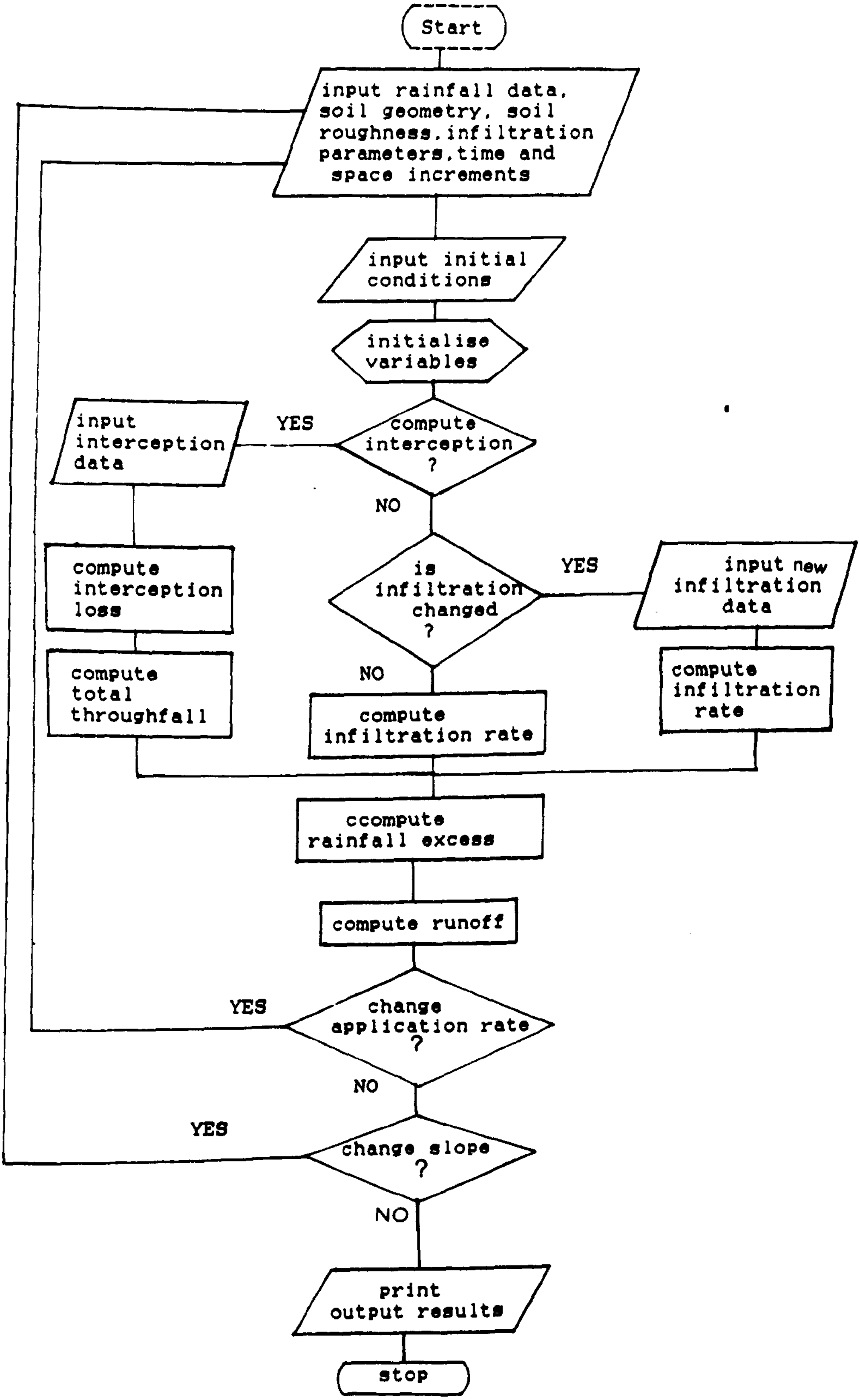


Flow chart of the model.

APPENDIX A.1.

APPENDIX A.2

PROGRAMMING SYMBOLS

```
C           A COMPUTER PROGRAM TO SIMULATE THE SURFACE RUNOFF
C           FROM SMALL PLOTS AT DIFFERENT SOIL SLOPES.
C            THE MODEL INCLUDES VARIABLE SOIL INFILTRATION
C            CONDITIONS, AND VARIABLE IRRIGATION APPLICATION
C           RATES. THE MODEL IS BASED ON THE KINEMATIC WAVE
C            EQUATIONS, AND USES THE FOUR-POINT IMPLICIT
C            NUMERICAL METHOD. ALSO THE MODEL CALCULATE THE
C            AMOUNT OF WATER INTERCEPTED BY THE CROP CANOPY.
C
C---------- DEFINITIONS
C           DX = DISTANCE INCREMENT (M)
C           RAIN1, RAIN2 = IRRIGATION APPLICATION RATE (MM/HR)
C           D = EXPONENT FOR SURFACE RUNOFF THAT IS RELATED TO
C            SOIL SURFACE ROUGHNESS AND GEOMTRY
C           N = THE MANNING ROUGHNESS COEFFICIENT
C           S1, S2 = SOIL SLOPE (%)
C           K,N1,C = CONSTANTS FOR INFILTRATION RATE EAQUATION
C           L = SOIL PLOT LENGTH (M)
C           W = SOIL PLOT WIDTH (M)
C           DT1, DT2 = TIME INCREMENTS (SECONDS)
C           H10,H30 = INITIAL DEPTHS OF SURFACE RUNOFF AT 10
C                     AND 30% SLOPES, RESPECTIVELY
C           T = TIME FROM BEGINNING OF IRRIGATION (SEC.)
C           FIL = INFILTRATION RATE (MM/HR)
C           RX = IRRIGATION( RAINFALL) EXCESS (M/SEC)
C           H1,H2,H3,H4 = SURFACE RUNOFF DEPTHS WITH DIFFERENT
C                         APPLICATION RATES ON DIFFERENT SLOPES (M)
C           Q1,Q2,Q3,Q4 = DISCHARGE PER UNIT WIDTH (M2/SEC)
C           RNO1,RNO2,RNO3,RNO4 = ACCUMULATIVE SURFACE RUNOFF
C                                 DEPTH (MM)
C           RUN1,RUN2,RUN3,RUN4 = SURFACE RUNOFF RATE (MM/HR)
C           K,B = DRAINAGE PARAMETERS FROM THE CROP CANOPY
C           P = THE FREE THROUGHFALL COEFFICIENT (%)
C           R = THE RATE AT WHICH IRRIGATION(RAIN) IS ADDED TO THE
C               CANOPY(MM/HR)
C           C1,C2,C3 = THE DEPTH OF WATER STORED ON THE CROP CANOPY
C                      DURING IRRIGATION FOR DIFFERENT APPLICATION
C                      RATES (MM)
C           REDPTH1,RDEPTH2,RDEPTH3 = DRIP RATE FROM THE CROP CANOPY
C            (MM/HR)
C
```

APPENDIX 1.2 (CONTINUED)

PROGRAM LISTING

```
      CHARACTER ANS1,ANS2,ANS3
      REAL L,N,K,N1
      DIMENSION T(9000),RX(9000),TX(9000),H10(9000),H30(9000),
     + H1(9000,2),H2(9000,2),Q1(9000,2),Q2(9000,2),
     + RNO1(9000),RNO2(9000),RNO3(9000),RNO4(9000),
     + RUN1(9000),RUN2(9000),RUN3(9000),RUN4(9000),
     + F1(9000),FF1(9000),F2(9000),FF2(9000),
     + DIF1(9000),DIFF1(9000),DIF2(9000),DIFF2(9000),
     + F3(9000),FF3(9000),DIF3(9000),DIFF3(9000),
     + F4(9000),FF4(9000),DIF4(9000),DIFF4(9000),
     + H3(9000,2),H4(9000,2),Q3(9000,2),Q4(9000,2)
      COMMON DX,RAIN1,RAIN2,D,N,S1,S2,C,Z,L,W
        OPEN(6,FILE='SROF.DAT',STATUS='NEW')
        OPEN(7,FILE='SROFF.DAT',STATUS='OLD')
        READ(7,*)DX,DT1,DT2,D,N,K,N1,C,Z
        READ(7,*)L,W,HH1,HH2,HH3,HH4
        B1=DX
1000    CALL OPTION(RAIN,SLOPE)
        WRITE(6,115)
115     FORMAT(5X,'CALCULATION OF SURFACE RUNOFF AT DIFFERENT
     * SOIL SLOPES AND APPLICAION RATES')
        WRITE(6,*)
        WRITE(6,550)RAIN,SLOPE
550     FORMAT(5X,'APPLICATION RATE (MM/HR) = ',F5.1,//10X,
     *'SOIL SLOPE =',F5.2//)
        S=SLOPE
        IF(S.EQ.0.1.AND.RAIN.EQ.300.0) GO TO 500
        IF(S.EQ.0.3.AND.RAIN.EQ.300.0) GO TO 600
        IF(RAIN.GT.300.0) GO TO 700
C---------FIND THE OVERLAND FLOW DEPTH & SURFACE RUN-OFF
C--------- UNDER APPLICATION RATE OF 300MM/HR.
C--FIND THE ZERO ROOTS OF THE EQUATION USING THE
C--NEWTON-RAPHSON METHOD
500     ALPHA1=(S**0.5)/N
        A1=2.0*DT1*ALPHA1
        DO 3 I=1,9000,8
        T(I)=FLOAT(I)
        H10(I)=FLOAT(I)*HH1
        AX=(T(I))/3600.0
        AX=AX**(-N1)
        FIL=(K*AX)+C
        RX(I)=(RAIN-FIL)/Z
        IF (RX(I).LE.0.0)GO TO 3
        R1=2.0*DX*DT1*RX(I)
        F1(I)=A1*(H10(I)**D)+B1*H10(I)-R1
        FF1(I)=D*A1*(H10(I)**(D-1.0))+B1
        DIF1(I)=H10(I)-(F1(I)/FF1(I))
        DIFF1(I)=DIF1(I)-DIF1(I-8)
        IF(F1(I).LT.1.0E-8)GO TO 50
```

```
          HH1=HH1*0.1
3         CONTINUE
C-----CALCULATE THE SURFACE RUNOFF FOR APPLICATION RATE
C-----300 MM/HR & SOIL SLOPE OF 10%
50        DO 10 J=1,2
          DO 10 I=1,9000,3
          T(I)=FLOAT(I)
          H1(I,J)=FLOAT(I)*HH1
          AX=(T(I))/3600.0
          AX=AX**(-N1)
          FIL=(K*AX)+C
          RX(I)=(RAIN-FIL)/Z
          IF (RX(I).LE.0.0)GO TO 10
          IF(J.EQ.1.OR.I.EQ.1)THEN
          H1(I,J)=0.0
          Q1(I,J)=0.0
          ELSE IF(I.NE.1.AND.J.EQ.2)THEN
          Q1(I,J)=ALPHA1*(H1(I,J)**D)
          RNO1(I)=((Q1(I,J))/(W*L))*3600.0*1000.0
          RUN1(I)=RNO1(I)*(T(I)/3600.0)
          TX(I)=T(I)/60.0
          END IF
10        CONTINUE
          WRITE(6,201)
201       FORMAT(5X,'TIME',20X,'RUN-OFF',28X,'RUN-OFF'/
     * 5X,'(MIN)',19X,'(MM/HR)',29X,'(MM)'//)
202       FORMAT(3X,F5.2,18X,F8.3,23X,F8.3)
          DO 30 I=1,9000,3
          TX(I)=T(I)/60.0
          WRITE(6,202)TX(I),RNO1(I),RUN1(I)
30        CONTINUE
          GO TO 900
C--FIND THE ZERO ROOTS OF THE EQUATION USING THE
C--NEWTON-RAPHSON METHOD
600       ALPHA2=(S**0.5)/N
          A2=2.0*DT1*ALPHA2
          DO 13 I=1,9000,3
          T(I)=FLOAT(I)
          H30(I)=FLOAT(I)*HH2
          AX=(T(I))/3600.0
          AX=AX**(-N1)
          FIL=(K*AX)+C
          RX(I)=(RAIN-FIL)/Z
          IF (RX(I).LE.0.0)GO TO 13
          R2=2.0*DT1*DX*RX(I)
          F2(I)=A2*(H30(I)**D)+B1*H30(I)-R2
          FF2(I)=D*A2*(H30(I)**(D-1.0))+B1
          DIF2(I)=H30(I)-F2(I)/FF2(I)
          DIFF2(I)=DIF2(I)-DIF2(I-3)
          IF(F2(I).LT.1.0E-08)GO TO 150
          HH2=HH2*0.1
13         CONTINUE
C-----CALCULATE THE SURFACE RUNOFF FOR APPLICATION
C-----RATE 300 MM/HR & SOIL SLOPE OF 30%
150        DO 11 J=1,2
          DO 11 I=1,9000,3
          T(I)=FLOAT(I)
          H2(I,J)=FLOAT(I)*HH2
```

```
      AX=(T(I))/3600.0
      AX=AX**(-N1)
      FIL=(K*AX)+C
      RX(I)=(RAIN-FIL)/Z
      IF (RX(I).LE.0.0)GO TO 11
      IF(J.EQ.1.OR.I.EQ.1)THEN
      H2(I,J)=0.0
      Q2(I,J)=0.0
      ELSE IF(I.NE.1.AND.J.EQ.2)THEN
      TX(I)=T(I)/60.0
      Q2(I,J)=ALPHA2*(H2(I,J)**D)
      RNO2(I)=((Q2(I,J))/(W*L))*3600.0*1000.0
      RUN2(I)=RNO2(I)*(T(I)/3600.0)
      END IF
 11   CONTINUE
      WRITE(6,206)
 206  FORMAT(5X,'TIME',20X,'RUN-OFF',28X,'RUN-OFF'/
     * 5X,'(MIN)',19X,'(MM/HR)',29X,'(MM)'//)
 208  FORMAT(3X,F6.2,18X,F8.3,28X,F8.3)
      DO 35 I=1,7800,8
      TX(I)=T(I)/60.0
      WRITE(6,208)TX(I),RNO2(I),RUN2(I)
 35   CONTINUE
       GO TO 900
C---------FIND THE OVERLAND FLOW DEPTH & SURFACE RUN-OFF
C---------UNDER APPLICATION RATE OF 482MM/HR.
C
C------FIND THE ZERO ROOTS OF THE EQUATION USING THE
C------NEWTON-RAPHSON METHOD FOR APPLICATION RATE 482
C------MM/HR & SLOPE 10%
 700  S=SLOPE
      ALPHA1=(S**0.5)/N
      A3=2.0*DT2*ALPHA1
      ALPHA2=(S**0.5)/N
      A4=2.0*DT2*ALPHA2
      DO 14 I=1,90000,4
      T(I)=FLOAT(I)
      H10(I)=FLOAT(I)*HH3
      AX=(T(I))/3600.0
      AX=AX**(-N1)
      FIL=(K*AX)+C
      RX(I)=(RAIN-FIL)/Z
      IF (RX(I).LE.0.0)GO TO 14
      R3=2*DX*DT2*RX(I)
      F3(I)=A3*(H10(I)**D)+B1*H10(I)-R3
      FF3(I)=D*A3*(H10(I)**(D-1.0))+B1
      DIF3(I)=H10(I)-F3(I)/FF3(I)
      DIFF3(I)=DIF3(I)-DIF3(I-4)
      IF(F3(I).LT.1.0E-9)GO TO 60
      HH3=HH3*0.1
C--FIND THE ZERO ROOTS OF THE EQUATION USING THE
C--NEWTON-RAPHSON METHOD FOR APPLICATION RATE 482
C--MM/HR & SLOPE 30%
      H30(I)=FLOAT(I)*HH4
      T(I)=FLOAT(I)
      AX=(T(I))/3600.0
      AX=AX**(-N1)
      FIL=(K*AX)+C
```

```
      RX(I)=(RAIN-FIL)/Z
      IF (RX(I).LE.0.0)GO TO 14
      R4=2*DX*DT2*RX(I)
      F4(I)=A4*(H30(I)**D)+B1*H30(I)-R4
      FF4(I)=D*A4*(H30(I)**(D-1.0))+B1
      DIF4(I)=H30(I)-F4(I)/FF4(I)
      DIFF4(I)=DIF4(I)-DIF4(I-4)
      IF(F4(I).LT.1.0E-9)GO TO 60
      HH4=HH4*0.1
14     CONTINUE
60    IF(S.EQ.0.1) GO TO 70
      IF(S.EQ.0.3) GO TO 80
C-----CALCULATE THE SURFACE RUNOFF FOR APPLICATION
C----- RATE 482 MM/HR & SLOPE OF 10%
70    DO 20 J=1,2
      DO 20 I=1,6300,4
      T(I)=FLOAT(I)
      AX=(T(I))/3600.0
      AX=AX**(-N1)
      FIL=(K*AX)+C
      RX(I)=(RAIN-FIL)/Z
      IF (RX(I).LE.0.0)GO TO 20
      H3(I,J)=FLOAT(I)*HH3
      IF(J.EQ.1.OR.I.EQ.1)THEN
      H3(I,J)=0.0
      Q3(I,J)=0.0
      ELSE IF(I.NE.1.AND.J.EQ.2)THEN
      Q3(I,J)=ALPHA1*(H3(I,J)**D)
      RNO3(I)=((Q3(I,J))/(W*L))*3600.0*1000.0
      RUN3(I)=RNO3(I)*(T(I)/3600.0)
      TX(I)=T(I)/60.0
      END IF
20    CONTINUE
      WRITE(6,212)
212   FORMAT(5X,'TIME',20X,'RUN-OFF',28X,'RUN-OFF'/
    * 5X,'(MIN)',19X,'(MM/HR)',29X,'(MM)'//)
214   FORMAT(3X,F6.2,18X,F8.3,28X,F8.3)
      DO 45 I=1,6300,4
      TX(I)=T(I)/60.0
      WRITE(6,214)TX(I),RNO3(I),RUN3(I)
45    CONTINUE
      GO TO 900
C-----CALCULATE THE SURFACE RUNOFF FOR APPLICATION
C-----RATE 482 MM/HR & SLOPE OF 30%
80    DO 22 J=1,2
      DO 22 I=1,6300,4
      T(I)=FLOAT(I)
      AX=(T(I))/3600.0
      AX=AX**(-N1)
      FIL=(K*AX)+C
      RX(I)=(RAIN-FIL)/Z
      IF (RX(I).LE.0.0)GO TO 22
      H4(I,J)=FLOAT(I)*HH3
      IF(J.EQ.1.OR.I.EQ.1)THEN
      H4(I,J)=0.0
      Q4(I,J)=0.0
      ELSE IF(I.NE.1.AND.J.EQ.2)THEN
      Q4(I,J)=ALPHA2*(H4(I,J)**D)
```

```
      RNO4(I)=((Q4(I,J))/(W*L))*3600.0*1000.0
      RUN4(I)=RNO4(I)*(T(I)/3600.0)
      TX(I)=T(I)/60.0
      END IF
22    CONTINUE
      WRITE(6,218)
218   FORMAT(5X,'TIME',20X,'RUN-OFF',28X,'RUN-OFF'/
     * 5X,'(MIN)',19X,'(MM/HR)',29X,'(MM)'//)
220   FORMAT(3X,F6.2,18X,F8.3,28X,F8.3)
      DO 55 I=1,5161,4
      TX(I)=T(I)/60.0
      WRITE(6,220)TX(I),RNO4(I),RUN4(I)
55    CONTINUE
      WRITE(*,*)
900   WRITE(6,99)
99    FORMAT(5X,'DO YOU WANT MORE CALCULATION?(Y/N)')
      READ(5,'(A1)')ANS1
      IF(ANS1.EQ.'Y') GO TO 1000
      IF(ANS1.EQ.'N') GO TO 1100
      WRITE(*,*)
1100  WRITE(6,101)
101    FORMAT(5X,'DO YOU WANT TO CALCULATE THE RUNOFF
     *AT THE END OF THE IRRIGATION SEASON WITH DIFFERENT
     *INFILTARTION RATE ? (Y/N)')
      READ(5,'(A2)')ANS2
      IF (ANS2.EQ.'Y') CALL RUNOFF2(TX,RNO,RUN)
      IF (ANS2.EQ.'N') GO TO 1300
      WRITE(*,*)
1300  WRITE(6,102)
102   FORMAT(5X,'DO YOU WANT TO CALCULATE INTERCEPTION
     *LOSS BY CROP CANOPY DURING IRRIGATION ? (Y/N)')
      READ(5,'(A3)')ANS3
      IF(ANS3.EQ.'Y') CALL INCEPT(TIME,C)
      IF(ANS3.EQ.'N') GO TO 1500
1500  STOP
      END
C-- THIS SUBROUTINE CALCULATES THE SURFACE RUNOFF FROM
C----THE CATCHMENT WHEN THE INFILTARTION RATE HAS CHANGED
      SUBROUTINE RUNOFF2(TX,RNO,RUN)
      CHARACTER ANS
      REAL L,N,K,N1
      DIMENSION T(9000),RX(9000),TX(9000),H10(9000),H30(9000)
      DIMENSION H1(9000,2),H2(9000,2),Q1(9000,2),Q2(9000,2)
      DIMENSION RNO1(9000),RNO2(9000),RNO3(9000),RNO4(9000)
      DIMENSION RUN1(9000),RUN2(9000),RUN3(9000),RUN4(9000)
      DIMENSION F1(9000),FF1(9000),RR(9000),R1(9000),R2(9000)
      DIMENSION F2(9000),FF2(9000),DIF1(9000),DIFF1(9000)
      DIMENSION DIF2(9000),DIFF2(9000),F3(9000),FF3(9000)
      DIMENSION DIF3(9000),DIFF3(9000),F4(9000),FF4(9000)
      DIMENSION DIF4(9000),DIFF4(9000),H3(9000,2),H4(9000,2)
      DIMENSION Q3(9000,2),Q4(9000,2),R3(9000),R4(9000)
      OPEN(6,FILE='INF.DAT',STATUS='NEW')
      OPEN(7,FILE='KWM.DAT',STATUS='OLD')
      READ(7,*)DX,D,N,K,N1,C,Z,L,W
      READ(7,*)DT3,DT4,HH1,HH2,HH3,HH4
      B1=DX
400   CALL OPTION(RAIN,SLOPE)
      WRITE(6,115)
```

```
115       FORMAT(5X,'CALCULATION OF SURFACE RUNOFF AT DIFFERENT.
     * SOIL SLOPES AND APPLICAION RATES WITH DIFFERENT
     * INFILTRATION RATE')
          WRITE(6,*)
          WRITE (6,116)RAIN,SLOPE
116       FORMAT(5X,'APPLICATION RATE = ',F5.1,//10X,
     * ' SOIL SLOPE = ',F5.2//)
          S=SLOPE
          IF(RAIN.LE.300.0) GO TO 200
          IF(RAIN.GT.300.0)GO TO 210
C------CALCULATION OF SURFACE RUN-OFF UNDER APPLICATION
C------RATE OF 300 MM/HR.
200       ALPHA1=(S**0.5)/N
          A1=2.0*DT3*ALPHA1
          ALPHA2=(S**0.5)/N
          A2=2.0*DT3*ALPHA2
C--FIND THE ZERO ROOTS OF THE EQUATION USING THE
C--NEWTON-RAPHSON METHOD. FOR APPLICATION RATE OF
C--300 MM/HR
          DO 3 I=1,9000,1
          T(I)=FLOAT(I)*0.95
          H10(I)=FLOAT(I)*0.95*HH1
          H30(I)=FLOAT(I)*0.95*HH2
          AX=(T(I))/3600.0
          AX=AX**(-N1)
          FIL=(K*AX)+C
          RX(I)=(RAIN-FIL)/Z
          IF (RX(I).LE.0.0)GO TO 3
          R=2.0*DX*DT3*RX(I)
          F1(I)=A1*(H10(I)**D)+B1*H10(I)-R
          FF1(I)=D*A1*(H10(I)**(D-1.0))+B1
          DIF1(I)=H10(I)-(F1(I)/FF1(I))
          DIFF1(I)=DIF1(I)-DIF1(I-1)
          IF(F1(I).LT.1.0E-10)GO TO 50
          HH1=HH1*0.1
          F2(I)=A2*(H30(I)**D)+B1*H30(I)-R
          FF2(I)=D*A2*(H30(I)**(D-1.0))+B1
          DIF2(I)=H30(I)-F2(I)/FF2(I)
          DIFF2(I)=DIF2(I)-DIF2(I-1)
          IF(F2(I).LT.1.0E-10)GO TO 50
          HH2=HH2*0.1
3         CONTINUE
50        IF (S.EQ.0.1) GO TO 220
          IF (S.EQ.0.3) GO TO 230
C------- CALCULATE THE SURFACE RUNOFF FOR APPLICAATION
C--------RATE OF 300 MM/HR & SLOPE 10%
220       DO 10 J=1,2
          DO 10 I=1,9000,1
          H1(I,J)=FLOAT(I)*0.95*HH1
          T(I)=FLOAT(I)*0.95
          AX=(T(I))/3600.0
          AX=AX**(-N1)
          FIL=(K*AX)+C
          RX(I)=(RAIN-FIL)/Z
          IF (RX(I).LE.0.0)GO TO 10
          RR(I)=2.0*DT3*DX*RX(I)
          IF(J.EQ.1.OR.I.EQ.1)THEN
          H1(I,J)=0.0
```

```
          H2(I,J)=0.0
          Q1(I,J)=0.0
          Q2(I,J)=0.0
          ELSE IF(I.NE.1.AND.J.EQ.2)THEN
          Q1(I,J)=ALPHA1*(H1(I,J)**D)
          RNO1(I)=((Q1(I,J))/(W*L))*3600.0*1000.0
          RUN1(I)=RNO1(I)*(T(I)/3600.0)
          Q2(I,J)=ALPHA2*(H2(I,J)**D)
          RNO2(I)=((Q2(I,J))/(W*L))*3600.0*1000.0
          RUN2(I)=RNO2(I)*(T(I)/3600.0)
          END IF
10        CONTINUE
          WRITE(6,102)
102       FORMAT(5X,'TIME',20X,'RUN-OFF',28X,'RUN-OFF'/
     *    5X,'(MIN)',19X,'(MM/HR)',29X,'(MM)'//)
104       FORMAT(3X,F8.3,18X,F8.3,23X,F8.3)
          DO 130 I=1,2500,1
          TX(I)=T(I)/60.0
           WRITE(6,104)TX(I),RNO1(I),RUN1(I)
130        CONTINUE
          GO TO 300
C-------- CALCULATE THE SURFACE RUNOFF FOR APPLICAATION
C---------RATE OF 300 MM/HR & SLOPE 30%
230       DO 20 J=1,2
          DO 20 I=1,9000,1
          H2(I,J)=FLOAT(I)*0.95*HH2
          T(I)=FLOAT(I)*0.95
          AX=(T(I))/3600.0
          AX=AX**(-N1)
          FIL=(K*AX)+C
          RX(I)=(RAIN-FIL)/Z
          IF (RX(I).LE.0.0)GO TO 20
          RA(I)=2.0*DT3*DX*RX(I)
          IF(J.EQ.1.OR.I.EQ.1)THEN
          H2(I,J)=0.0
          Q2(I,J)=0.0
          ELSE IF(I.NE.1.AND.J.EQ.2)THEN
          Q2(I,J)=ALPHA2*(H2(I,J)**D)
          RNO2(I)=((Q2(I,J))/(W*L))*3600.0*1000.0
          RUN2(I)=RNO2(I)*(T(I)/3600.0)
          END IF
20        CONTINUE
          WRITE(6,106)
106       FORMAT(5X,'TIME',20X,'RUN-OFF',28X,'RUN-OFF'/
     *    5X,'(MIN)',19X,'(MM/HR)',29X,'(MM)'//)
107       FORMAT(3X,F8.3,18X,F8.3,23X,F8.3)
          DO 35 I=1,1920,1
          TX(I)=T(I)/60.0
           WRITE(6,107)TX(I),RNO2(I),RUN2(I)
35        CONTINUE
          GO TO 300
C-----CALCULATIONS OF SURFACE RUN-OFF UNDER APPLICATION
C-----RATE OF 482 MM/HR.
210       S=SLOPE
          ALPHA1=(S**0.5)/N
          A3=2.0*DT4*ALPHA1
          ALPHA2=(S**0.5)/N
          A4=2.0*DT4*ALPHA2
```

```
C--FIND THE ZERO ROOTS OF THE EQUATION USING THE
C--NEWTON-RAPHSON METHOD
         DO 4 I=1,9000,1
         H10(I)=FLOAT(I)*0.24*HH3
         H30(I)=FLOAT(I)*0.24*HH4
         T(I)=FLOAT(I)*0.24
         AX=(T(I))/3600.0
         AX=AX**(-N1)
         FIL=(K*AX)+C
         RX(I)=(RAIN-FIL)/Z
         IF (RX(I).LE.0.0)GO TO 4
         RC=2*DX*DT4*RX(I)
         F3(I)=A3*(H10(I)**D)+B1*H10(I)-RC
         FF3(I)=D*A3*(H10(I)**(D-1.0))+B1
         DIF3(I)=H10(I)-F3(I)/FF3(I)
         DIFF3(I)=DIF3(I)-DIF3(I-1)
         IF(F3(I).LT.1.0E-3)GO TO 60
         HH3=HH3*0.1
         F4(I)=A4*(H30(I)**D)+B1*H30(I)-RC
         FF4(I)=D*A4*(H30(I)**(D-1.0))+B1
         DIF4(I)=H30(I)-F4(I)/FF4(I)
         DIFF4(I)=DIF4(I)-DIF4(I-1)
         IF(F4(I).LT.1.0E-3)GO TO 60
         HH4=HH4*0.1
4        CONTINUE
60       IF(S.EQ.0.1.AND.RAIN.EQ.482.0) GO TO 240
         IF(S.EQ.0.3) GO TO 250
C---CALCULATE THE SURFACE RUNOFF FOR APPLICAATION
C---RATE OF 482 MM/HR
C------- & SLOPE 10%
240      DO 30 J=1,2
         DO 30 I=1,8250,1
         T(I)=FLOAT(I)*0.24
         H3(I,J)=FLOAT(I)*0.24*HH3
         AX=(T(I))/3600.0
         AX=AX**(-N1)
         FIL=(K*AX)+C
         RX(I)=(RAIN-FIL)/Z
         IF (RX(I).LE.0.0)GO TO 30
         RC=2*DX*DT4*RX(I)
         IF(J.EQ.1.OR.I.EQ.1)THEN
         H3(I,J)=0.0
         Q3(I,J)=0.0
         ELSE IF(I.NE.1.AND.J.EQ.2)THEN
         Q3(I,J)=ALPHA1*(H3(I,J)**D)
         RNO3(I)=((Q3(I,J))/(W*L))*3600.0*1000.0
         RUN3(I)=RNO3(I)*(T(I)/3600.0)
         END IF
30       CONTINUE
         WRITE(6,112)
112      FORMAT(5X,'TIME',20X,'RUN-OFF',28X,'RUN-OFF'/
      * 5X,'(MIN)',19X,'(MM/HR)',29X,'(MM)'//)
114      FORMAT(3X,F8.3,18X,F8.3,23X,F8.3)
         DO 45 I=1,8250,1
         TX(I)=T(I)/60.0
         WRITE(6,114)TX(I),RNO3(I),RUN3(I)
45       CONTINUE
         GO TO 300
```

```
C----CALCULATE THE SURFACE RUNOFF FOR APPLICAATION
C----RATE OF 482 MM/HR
C------- & SLOPE 30%
250       DO 40 J=1,2
          DO 40 I=1,8250,1
          T(I)=FLOAT(I)*0.24
          H4(I,J)=FLOAT(I)*0.24*HH4
          AX=(T(I))/3600.0
          AX=AX**(-N1)
          FIL=(K*AX)+C
          RX(I)=(RAIN-FIL)/Z
          IF (RX(I).LE.0.0)GO TO 40
          RC=Z*DX*DT4*RX(I)
          IF(J.EQ.1.OR.I.EQ.1)THEN
          H4(I,J)=0.0
          Q4(I,J)=0.0
          ELSE IF(I.NE.1.AND.J.EQ.2)THEN
          Q4(I,J)=ALPHA2*(H4(I,J)**D)
          RNO4(I)=((Q4(I,J))/(W*L))*3600.0*1000.0
          RUN4(I)=RNO4(I)*(T(I)/3600.0)
          END IF
40        CONTINUE
          WRITE(6,120)
120       FORMAT(3X,F8.3,18X,F8.3,23X,F8.3)
          DO 55 I=1,7000,1
          TX(I)=T(I)/60.0
          WRITE(6,120)TX(I),RNO4(I),RUN4(I)
55        CONTINUE
          WRITE(*,*)
300       WRITE(6,90)
90        FORMAT (5X,'DO YOU WANT MORE CALCULATION ?(Y/N)')
          READ(5,'(A1)')ANS
          IF(ANS.EQ.'Y') GO TO 400
          IF(ANS.EQ.'N') GO TO 410
          RETURN
410       END
C---THIS SUBROUTINE CALCULATES THE AMOUNT OF WATER
C---INTERCEPTED BY THE CROP CANOPY DURING IRRIGATION
C---UNDER DIFFERENT APPLICTION RATES. IT ALSO CAN
C---CALCULATE THROUGHFALL
      SUBROUTINE INCEPT(TIME,C)
      REAL K
      CHARACTER ANS
      DIMENSION C1(200),C2(200),C3(200)
      DIMENSION TFALL1(200),RDEPTH1(200),TFALL2(200)
      DIMENSION RDEPTH2(200),TFALL3(200),RDEPTH3(200)
      OPEN(7,FILE='INCEPT.DAT',STATUS='OLD')
      OPEN(6,FILE='CEPT.DAT',STATUS='NEW')
      READ(7,*)K,B,P
120   CALL OPTION2(RAIN)
      WRITE(6,80)
80    FORMAT(5X,'CALCULATION OF THE AMOUNT OF WATER
     * INTERCEPTED',//5X,'AND STORED ON THE CROP CANOPY
     * DURING IRRIGATION FROM',//5X,'DIFFERENT
     * APPLICATION RATE.')
      WRITE(*,*)
      WRITE(*,*)
      WRITE(6,90)
```

```
 90     FORMAT(5X,'IRRIGATION DUARATION ',10X,' WATER STORED'
      * ,/11X,'(SEC)',29X,'(MM)'//)
 140    FORMAT(10X,F10.5,22X,F10.5)
        IF(RAIN.LT.100) GO TO 100
        IF(RAIN.GE.100) GO TO 60
C--CALCULATIONS OF WATER STORAGE(C) + FREE THROUGHFALL(F)
 60     T=0.00139
        R2=(1-P)*RAIN
        F2=RAIN-R2
        DO 25 I =1,15
        X1=ALOG(R2)+B*(C2(I-1)+(T*R2))
        X2=K*(EXP(B*(C2(I-1)+(T*R2))))
        X3=K*(EXP(B*(C2(I-1))))
        X4=R2
        C2(I)=(X1-ALOG(X2-X3+X4))/B
C---CALCULATE THE CROP CANOPY DRAINAGE RATE
        X5=EXP(B*C2(I))
        DRAIN2=K*X5
        TFALL2(I)=(F2+DRAIN2)*T
        TFALL22=TFALL2(I-1)+TFALL2(I)
        RDEPTH2(I)=RAIN*T
        RDEPTH22=RDEPTH2(I-1)+RDEPTH2(I)
        TIME2=T*3600.0
        WRITE(6,140)TIME2,C2(I)
        T=T+0.00139
 25     CONTINUE
 100    WRITE(6,110)
 110    FORMAT(5X,'DO YOU WANT TO CHANGE IRRIGATION
      * APPLICATION RATE ? (Y/N)')
        READ(5,'(A)')ANS
        IF(ANS.EQ.'Y') GO TO 120
        IF(ANS.EQ.'N') GO TO 130
        RETURN
 130    END
C--THIS SUBROUTINE DISPLAYS TO DEFAULTS APPLICATION
C--RATE AND SOIL SLOPE ON THE SCREEN. IT ALSO REQUESTS
C--THE USER WHETHER THE DEFAULTS  VALUES OR ONE OF
C--THEM TO BE CHANGED. ALSO IT CAN BE SEEN ON THE
C--SCREEN THE NEW VALUES FOR THE APPLICATION
C--RATE AND SOIL SLOPE.
        SUBROUTINE OPTION(RAIN,SLOPE)
        INTEGER WRONG
        INTEGER*4 PBID,VDID,ROWS,COLS,STATUS,
      &         SMG$CREATE_PASTEBOARD,
      &         SMG$CREATE_VIRTUAL_DISPLAY,
      &         SMG$PASTE_VIRTUAL_DISPLAY,
      &         SMG$PUT_LINE,SMG$SET_CURSOR_ABS,
      &         LIB$WAIT,SMG$DELETE_VIRTUAL_DISPLAY,
      &         SMG$ERASE_PASTEBOARD,
      &         SMG$PUT_CHARS,SMG$PUT_LINE_WIDE
        REAL RAIN,SLOPE
        CHARACTER *10 CRAIN,CSLOPE
          RAIN=100.0
          SLOPE=0.10
C   SET DEFAULT VALUES
        STATUS=SMG$CREATE_PASTEBOARD(PBID,'SYS$OUTPUT',ROWS,COLS)
        STATUS=SMG$CREATE_VIRTUAL_DISPLAY(ROWS,COLS,VDID)
        STATUS=SMG$PASTE_VIRTUAL_DISPLAY(VDID,PBID,1,1)
```

```
      STATUS=SMG$SET_CURSOR_ABS(VDID,1,1)
      STATUS=SMG$PUT_LINE_WIDE(VDID,
     & 'SURFACE RUNOFF CALCULATION ',0,1)
        WRITE(CRAIN,'(F5.1)')RAIN
        STATUS=SMG$SET_CURSOR_ABS(VDID,8,5)
        STATUS=SMG$PUT_LINE(VDID,'1.APPLICATION RATE (MM/HR) = '
     &                                           //CRAIN)
        WRITE(CSLOPE,'(F5.1)')SLOPE
        STATUS=SMG$SET_CURSOR_ABS(VDID,10,5)
        STATUS=SMG$PUT_LINE(VDID,'2. SOIL SLOPE = '//CSLOPE)
        WRONG=-1
        DO WHILE (WRONG.NE.0)
         CALL TEST(VDID,WRONG,1,2)
         IF (WRONG.NE.0) THEN
             STATUS=SMG$SET_CURSOR_ABS(VDID,21,1)
             STATUS=SMG$PUT_LINE(VDID,'
     &                                                 ')
             STATUS=SMG$SET_CURSOR_ABS(VDID,22,16)
             STATUS=SMG$PUT_LINE(VDID,'ENTER CORRECT VALUE FOR ',0,1)
             IF (WRONG.EQ.1) THEN
            CALL INPUTREAL(VDID,8,5,'1.APPLICATION RATE (MM/HR) = ',
     &                                         40,RAIN,1.0,800.0)
        ELSE IF (WRONG.EQ.2) THEN
            CALL INPUTREAL(VDID,10,5,'2. SOIL SLOPE )= ',
     &                                         34,SLOPE,0.10,5.0)
             END IF
         END IF
      END DO
        STATUS=SMG$DELETE_VIRTUAL_DISPLAY(VDID)
        STATUS=SMG$ERASE_PASTEBOARD(PBID)
        RETURN
        END

      SUBROUTINE INPUTCHAR(VDID,ROW,STCOL,TEXT,COL,VARIABLE)
      IMPLICIT NONE
      INTEGER ROW,STCOL,COL
      CHARACTER*(*) TEXT,VARIABLE
      INTEGER*4 VDID
      CALL ENTER(VDID,ROW,STCOL,TEXT,COL)
      READ(5,'(A)')VARIABLE
      RETURN
      END

      SUBROUTINE INPUTINT(VDID,ROW,STCOL,TEXT,COL,VARIABLE,
     &LLIMIT,ULIMIT)
      IMPLICIT NONE
      INTEGER ROW,STCOL,COL,VARIABLE,LLIMIT,ULIMIT
      CHARACTER*(*) TEXT
      INTEGER*4 VDID
      CALL ENTER(VDID,ROW,STCOL,TEXT,COL)
      READ(5,*,ERR=100)VARIABLE
      DO WHILE (VARIABLE.LT.LLIMIT.OR.VARIABLE.GT.ULIMIT)
100     CALL ERROR(VDID,ROW,COL)
        READ(5,*,ERR=100)VARIABLE
      END DO
      RETURN
      END
```

```
      SUBROUTINE INPUTREAL(VDID,ROW,STCOL,TEXT,COL,VARIABLE,
     &LLIMIT,ULIMIT)
      IMPLICIT NONE
      INTEGER ROW,STCOL,COL
      REAL VARIABLE,LLIMIT,ULIMIT
      CHARACTER*(*) TEXT
      INTEGER*4 VDID
      CALL ENTER(VDID,ROW,STCOL,TEXT,COL)
      READ(5,*,ERR=100)VARIABLE
      DO WHILE (VARIABLE.LT.LLIMIT.OR.VARIABLE.GT.ULIMIT)
100     CALL ERROR(VDID,ROW,COL)
         READ(5,*,ERR=100)VARIABLE
      END DO
      RETURN
      END

      SUBROUTINE TEST(VDID,WRONG,LLIMIT,ULIMIT)
      IMPLICIT NONE
      INTEGER WRONG,LLIMIT,ULIMIT
      INTEGER*4 VDID,SMG$PUT_LINE,SMG$SET_CURSOR_ABS,STATUS
      STATUS=SMG$SET_CURSOR_ABS(VDID,21,1)
      STATUS=SMG$PUT_LINE(VDID,'ENTER NUMBER CORRESPONDING TO
     &PARAMETER WITH INCORRECT VALUE ')
        CALL ENTER(VDID,22,15,'     (0=NO CHANGE) :      ',40)
      READ(5,*,ERR=100)WRONG
      DO WHILE (WRONG.NE.0.AND.(WRONG.LT.LLIMIT.OR.
     &          WRONG.GT.ULIMIT))
100     CALL ERROR(VDID,22,40)
         READ(5,*,ERR=100)WRONG
      END DO
      RETURN
      END

      SUBROUTINE ENTER(VDID,ROW,STCOL,TEXT,COL)
      IMPLICIT NONE
      INTEGER ROW,STCOL,COL
      CHARACTER*(*) TEXT
      INTEGER*4 VDID,STATUS,SMG$SET_CURSOR_ABS,SMG$PUT_LINE
      STATUS=SMG$SET_CURSOR_ABS(VDID,ROW,STCOL)
      STATUS=SMG$PUT_LINE(VDID,TEXT)
      STATUS=SMG$SET_CURSOR_ABS(VDID,ROW,COL)
      STATUS=SMG$PUT_LINE(VDID,'-',0)
      STATUS=SMG$SET_CURSOR_ABS(VDID,ROW,COL)
      STATUS=SMG$PUT_LINE(VDID,' ',0)
      STATUS=SMG$SET_CURSOR_ABS(VDID,ROW,COL)
      RETURN
      END

      SUBROUTINE ERROR(VDID,ROW,COL)
      IMPLICIT NONE
      INTEGER ROW,COL
      INTEGER*4 VDID,STATUS,SMG$SET_CURSOR_ABS,
     &          SMG$PUT_LINE,LIB$WAIT
      STATUS=SMG$SET_CURSOR_ABS(VDID,ROW,COL)
      STATUS=SMG$PUT_LINE(VDID,'DATA UNACCEPTABLE',0,1)
      STATUS=SMG$SET_CURSOR_ABS(VDID,ROW,COL-1)
      STATUS=LIB$WAIT(3.0)
      STATUS=SMG$SET_CURSOR_ABS(VDID,ROW,COL)
```

```
      STATUS=SMG$PUT_LINE(VDID,' ',0)
      STATUS=SMG$SET_CURSOR_ABS(VDID,ROW,COL)
      RETURN
      END

C--THIS SUBROUTINE DISPLAYS TO DEFAULTS APPLICATION
C--RATE ON THE SCREEN. IT ALSO REQUESTS
C--THE USER WHETHER THE DEFAULTS  VALUE WANTS TO BE
C--CHANGED. ALSO IT CAN BE SEEN ON THE
C--SCREEN THE NEW VALUE.
      SUBROUTINE OPTION2(RAIN)
      INTEGER WRONG
      INTEGER*4 PBID,VDID,ROWS,COLS,STATUS,SMG$CREATE_PASTEBOARD,
     &        SMG$CREATE_VIRTUAL_DISPLAY,SMG$PASTE_VIRTUAL_DISPLAY,
     &        SMG$PUT_LINE,SMG$SET_CURSOR_ABS,
     &        LIB$WAIT,SMG$DELETE_VIRTUAL_DISPLAY,SMG$ERASE_PASTEBOA
     &        SMG$PUT_CHARS,SMG$PUT_LINE_WIDE
      REAL RAIN
      CHARACTER *10 CRAIN
        RAIN=100.0
C   SET DEFAULT VALUES
      STATUS=SMG$CREATE_PASTEBOARD(PBID,'SYS$OUTPUT',ROWS,COLS)
      STATUS=SMG$CREATE_VIRTUAL_DISPLAY(ROWS,COLS,VDID)
      STATUS=SMG$PASTE_VIRTUAL_DISPLAY(VDID,PBID,1,1)
      STATUS=SMG$SET_CURSOR_ABS(VDID,1,1)
      STATUS=SMG$PUT_LINE_WIDE(VDID,
     & 'INTERCEPTION LOSS CALCULATION ',0,1)
        WRITE(CRAIN,'(F5.1)')RAIN
        STATUS=SMG$SET_CURSOR_ABS(VDID,8,5)
        STATUS=SMG$PUT_LINE(VDID,'1.APPLICATION RATE (MM/HR)= '
     &                                           //CRAIN)
        WRONG=-1
      DO WHILE (WRONG.NE.0)
         CALL TEST(VDID,WRONG,1,1)
         IF (WRONG.NE.0) THEN
            STATUS=SMG$SET_CURSOR_ABS(VDID,21,1)
            STATUS=SMG$PUT_LINE(VDID,'
     &                                                ')
            STATUS=SMG$SET_CURSOR_ABS(VDID,22,16)
            STATUS=SMG$PUT_LINE(VDID,'ENTER CORRECT VALUE FOR ',0,1)
            IF (WRONG.EQ.1) THEN
           CALL INPUTREAL(VDID,8,5,'1.APPLICATION RATE (MM/HR)= ',
     &                                       40,RAIN,1.0,800.0)
            END IF
         END IF
      END DO
        STATUS=SMG$DELETE_VIRTUAL_DISPLAY(VDID)
        STATUS=SMG$ERASE_PASTEBOARD(PBID)
        RETURN
        END
```

APPENDIX A.2 (CONTINUED)

TABLE 1 TYPICAL MODEL OUTPUT

RUNOFF COMPUTATION FROM SOIL A :

APPLICATION RATE (MM/HR) = 100.0
SOIL SLOPE = 0.30
TIME INCREMENT = 8 SECONDS
DISTANCE INCREMENT = 0.5 M

INFILTRATION EQUATION = $155.0\ T^{-0.25} + 20.0$

TIME (MIN)	RUN-OFF (MM/HR)	RUN-OFF (MM)	TIME (MIN)	RUN-OFF (MM/HR)	RUN-OFF (MM)	TIME (MIN)	RUN-OFF (MM/HR)	RUN-OFF (MM)	TIME (MIN)	RUN-OFF (MM/HR)	RUN-OFF (MM)
11.35	0.000	0.000	14.95	1.347	0.335	18.55	1.932	0.597	22.15	2.598	0.959
11.48	0.867	0.166	15.08	1.367	0.344	18.68	1.955	0.609	22.28	2.624	0.974
11.62	0.884	0.171	15.22	1.388	0.352	18.82	1.979	0.620	22.42	2.650	0.990
11.75	0.901	0.176	15.35	1.408	0.360	18.95	2.002	0.632	22.55	2.676	1.006
11.88	0.918	0.182	15.48	1.428	0.369	19.08	2.025	0.644	22.68	2.703	1.022
12.02	0.935	0.187	15.62	1.449	0.377	19.22	2.049	0.656	22.82	2.729	1.038
12.15	0.953	0.193	15.75	1.470	0.386	19.35	2.073	0.668	22.95	2.756	1.054
12.28	0.970	0.199	15.88	1.491	0.395	19.48	2.097	0.681	23.08	2.783	1.071
12.42	0.988	0.204	16.02	1.512	0.404	19.62	2.121	0.693	23.22	2.810	1.087
12.55	1.006	0.210	16.15	1.533	0.413	19.75	2.145	0.706	23.35	2.837	1.104
12.68	1.024	0.216	16.28	1.554	0.422	19.88	2.169	0.719	23.48	2.864	1.121
12.82	1.042	0.223	16.42	1.575	0.431	20.02	2.193	0.732	23.62	2.891	1.138
12.95	1.060	0.229	16.55	1.597	0.440	20.15	2.218	0.745	23.75	2.918	1.155
13.08	1.078	0.235	16.68	1.618	0.450	20.28	2.242	0.758	23.88	2.946	1.173
13.22	1.097	0.242	16.82	1.640	0.460	20.42	2.267	0.771	24.02	2.973	1.190
13.35	1.115	0.248	16.95	1.662	0.469	20.55	2.292	0.785	24.15	3.001	1.208
13.48	1.134	0.255	17.08	1.683	0.479	20.68	2.317	0.799	24.28	3.029	1.226
13.62	1.153	0.262	17.22	1.705	0.489	20.82	2.342	0.812	24.42	3.057	1.244
13.75	1.172	0.268	17.35	1.728	0.500	20.95	2.367	0.826	24.55	3.084	1.262
13.88	1.191	0.275	17.48	1.750	0.510	21.08	2.392	0.841	24.68	3.112	1.280
14.02	1.210	0.283	17.62	1.772	0.520	21.22	2.417	0.855	24.82	3.141	1.299
14.15	1.229	0.290	17.75	1.795	0.531	21.35	2.443	0.869	24.95	3.169	1.318
14.28	1.248	0.297	17.88	1.817	0.542	21.48	2.468	0.884	25.08	3.197	1.337
14.42	1.268	0.305	18.02	1.840	0.552	21.62	2.494	0.899	25.22	3.226	1.356
14.55	1.288	0.312	18.15	1.863	0.563	21.75	2.520	0.913	25.35	3.254	1.375
14.68	1.307	0.320	18.28	1.885	0.575	21.88	2.545	0.928	25.48	3.283	1.394
14.82	1.327	0.328	18.42	1.909	0.586	22.02	2.571	0.944	25.62	3.311	1.414

25.75	3.340	1.434	33.48	5.179	2.890	41.22	7.328	5.034	48.95	9.765	7.967
25.88	3.369	1.453	33.62	5.214	2.921	41.35	7.367	5.077	49.08	9.810	8.025
26.02	3.399	1.474	33.75	5.248	2.952	41.48	7.407	5.121	49.22	9.854	8.083
26.15	3.427	1.494	33.88	5.283	2.983	41.62	7.447	5.165	49.35	9.899	8.142
26.28	3.457	1.514	34.02	5.318	3.015	41.75	7.487	5.209	49.48	9.943	8.201
26.42	3.485	1.535	34.15	5.352	3.046	41.88	7.527	5.254	49.62	9.988	8.260
26.55	3.515	1.556	34.28	5.387	3.078	42.02	7.567	5.299	49.75	10.033	8.319
26.68	3.545	1.577	34.42	5.422	3.110	42.15	7.607	5.344	49.88	10.078	8.379
26.82	3.575	1.598	34.55	5.458	3.143	42.28	7.647	5.389	50.02	10.123	8.439
26.95	3.604	1.619	34.68	5.493	3.175	42.42	7.687	5.435	50.15	10.168	8.499
27.08	3.634	1.640	34.82	5.528	3.208	42.55	7.728	5.480	50.28	10.213	8.559
27.22	3.664	1.662	34.95	5.563	3.241	42.68	7.768	5.526	50.42	10.259	8.620
27.35	3.694	1.684	35.08	5.599	3.274	42.82	7.809	5.572	50.55	10.304	8.681
27.48	3.724	1.706	35.22	5.635	3.307	42.95	7.849	5.619	50.68	10.349	8.742
27.62	3.754	1.728	35.35	5.670	3.341	43.08	7.890	5.666	50.82	10.395	8.804
27.75	3.785	1.750	35.48	5.706	3.376	43.22	7.931	5.713	50.95	10.441	8.866
27.88	3.815	1.773	35.62	5.742	3.409	43.35	7.972	5.760	51.08	10.486	8.928
28.02	3.846	1.796	35.75	5.778	3.443	43.48	8.013	5.807	51.22	10.532	8.990
28.15	3.876	1.819	35.88	5.814	3.477	43.62	8.054	5.855	51.35	10.578	9.053
28.28	3.907	1.842	36.02	5.850	3.512	43.75	8.095	5.903	51.48	10.624	9.116
28.42	3.938	1.865	36.15	5.886	3.546	43.88	8.136	5.951	51.62	10.670	9.179
28.55	3.969	1.888	36.28	5.922	3.581	44.02	8.178	5.999	51.75	10.716	9.242
28.68	4.000	1.912	36.42	5.959	3.617	44.15	8.219	6.048	51.88	10.762	9.306
28.82	4.031	1.936	36.55	5.995	3.652	44.28	8.261	6.097	52.02	10.808	9.370
28.95	4.062	1.960	36.68	6.032	3.688	44.42	8.302	6.146	52.15	10.854	9.434
29.08	4.093	1.984	36.82	6.069	3.724	44.55	8.344	6.195	52.28	10.901	9.499
29.22	4.125	2.009	36.95	6.105	3.760	44.68	8.386	6.245	52.42	10.947	9.564
29.35	4.156	2.033	37.08	6.142	3.796	44.82	8.427	6.295	52.55	10.994	9.629
29.48	4.188	2.058	37.22	6.179	3.833	44.95	8.469	6.345	52.68	11.040	9.694
29.62	4.219	2.083	37.35	6.216	3.870	45.08	8.511	6.395	52.82	11.087	9.760
29.75	4.251	2.108	37.48	6.253	3.906	45.22	8.553	6.446	52.95	11.134	9.826
29.88	4.283	2.133	37.62	6.290	3.944	45.35	8.596	6.497	53.08	11.181	9.892
30.02	4.315	2.159	37.75	6.328	3.981	45.48	8.638	6.548	53.22	11.228	9.958
30.15	4.347	2.184	37.88	6.365	4.019	45.62	8.680	6.599	53.35	11.275	10.025
30.28	4.379	2.210	38.02	6.402	4.057	45.75	8.723	6.651	53.48	11.322	10.092
30.42	4.412	2.236	38.15	6.440	4.095	45.88	8.765	6.703	53.62	11.369	10.159
30.55	4.444	2.263	38.28	6.478	4.133	46.02	8.808	6.755	53.75	11.416	10.227
30.68	4.476	2.289	38.42	6.515	4.172	46.15	8.850	6.807	53.88	11.464	10.295
30.82	4.509	2.316	38.55	6.553	4.210	46.28	8.893	6.860	54.02	11.511	10.363
30.95	4.541	2.343	38.68	6.591	4.249	46.42	8.935	6.913	54.15	11.558	10.432
31.08	4.574	2.370	38.82	6.629	4.289	46.55	8.979	6.966	54.28	11.606	10.500
31.22	4.607	2.397	38.95	6.667	4.328	46.68	9.022	7.019	54.42	11.654	10.569
31.35	4.640	2.424	39.08	6.705	4.368	46.82	9.065	7.073	54.55	11.701	10.639
31.48	4.673	2.452	39.22	6.744	4.408	46.95	9.108	7.127	54.68	11.749	10.708
31.62	4.706	2.480	39.35	6.782	4.448	47.08	9.151	7.181	54.82	11.797	10.778
31.75	4.739	2.508	39.48	6.820	4.489	47.22	9.195	7.236	54.95	11.845	10.848
31.88	4.772	2.536	39.62	6.859	4.529	47.35	9.238	7.290	55.08	11.893	10.919
32.02	4.805	2.564	39.75	6.897	4.570	47.48	9.281	7.345	55.22	11.941	10.989
32.15	4.839	2.593	39.88	6.936	4.611	47.62	9.325	7.400	55.35	11.989	11.060
32.28	4.873	2.622	40.02	6.975	4.652	47.75	9.369	7.456	55.48	12.038	11.131
32.42	4.907	2.651	40.15	7.014	4.693	47.88	9.412	7.512	55.62	12.086	11.203
32.55	4.941	2.680	40.28	7.053	4.735	48.02	9.456	7.568	55.75	12.134	11.275
32.68	4.974	2.710	40.42	7.092	4.777	48.15	9.500	7.624	55.88	12.183	11.347
32.82	5.008	2.739	40.55	7.131	4.819	48.28	9.544	7.680	56.02	12.232	11.419
32.95	5.042	2.769	40.68	7.170	4.862	48.42	9.588	7.737	56.15	12.280	11.492
33.08	5.076	2.799	40.82	7.209	4.904	48.55	9.632	7.794	56.28	12.329	11.565
33.22	5.110	2.829	40.95	7.249	4.947	48.68	9.676	7.851	56.42	12.378	11.639
33.35	5.145	2.860	41.08	7.288	4.990	48.82	9.721	7.909	56.55	12.427	11.712

APPENDIX A.2 (CONTINUED)

COMPUTATION OF INTERCEPTION LOSS

APPLICATION RATE = 300 MM/HR

TIME (SEC)	INTERCEPTION LOSS (MM)
5.004000	0.3111761
10.00800	0.8815924
15.01200	1.104452
20.01600	1.106612
25.02000	1.106614
30.02400	1.106614
35.02800	1.106614
40.03200	1.106614
45.03600	1.106614
50.04000	1.106614
55.04400	1.106614
60.04800	1.106614
65.05200	1.106614
70.05601	1.106614

TABLE 2 TYPICAL MODEL OUTPUT

Figure 1 Soil moisture content distribution for tied furrow before fourth irrigation.
Application rate = 100 mm/hr

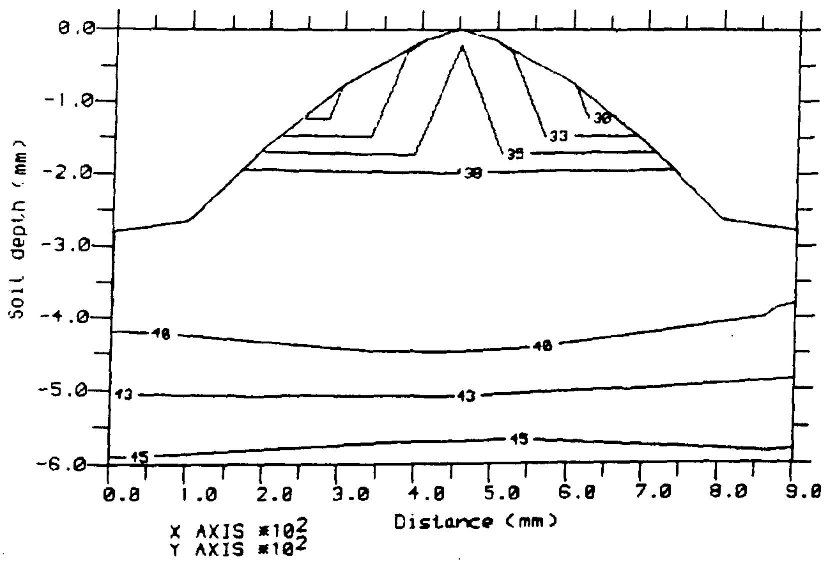
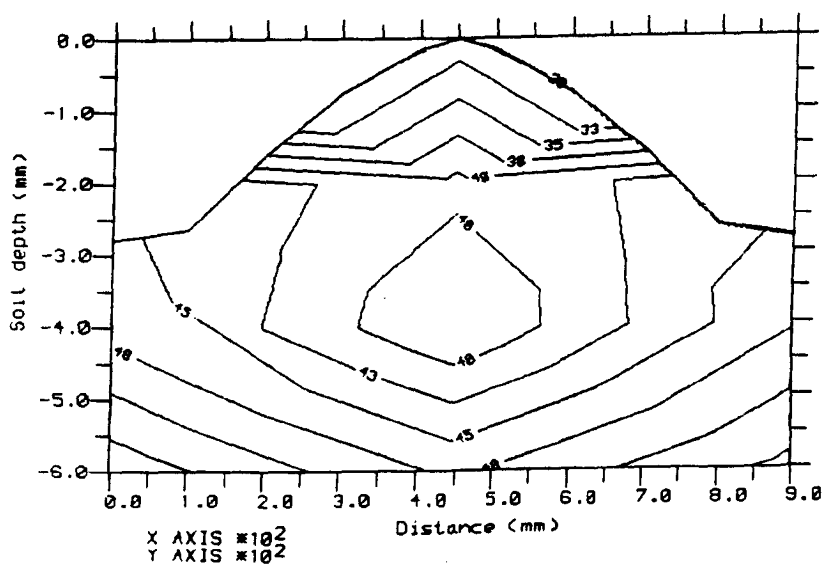


Figure 2 Soil moisture content distribution for tied furrow after fourth irrigation.
Application rate = 100 mm/hr



APPENDIX A.3

Figure 3 Soil moisture content distribution for tied furrow before fourth irrigation.
Application rate = 300 mm/hr

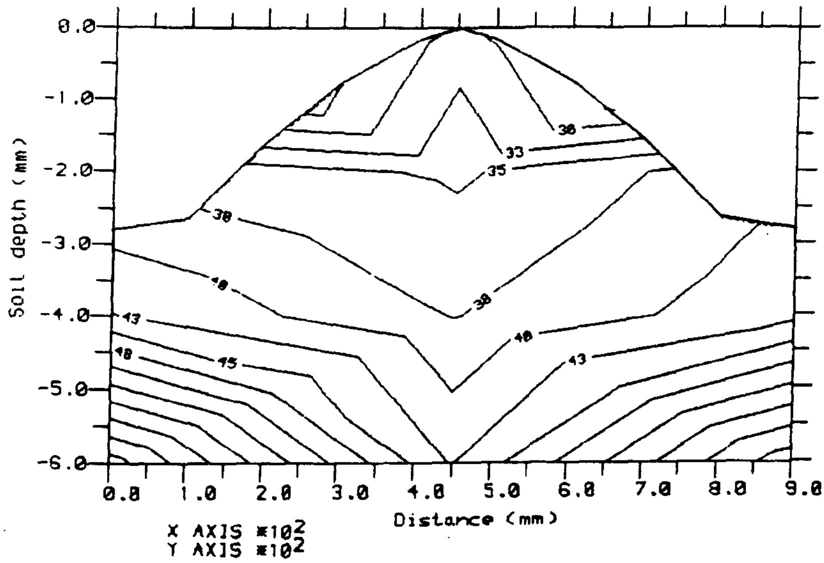


Figure 4 Soil moisture content distribution for tied furrow after fourth irrigation.
Application rate = 300 mm/hr

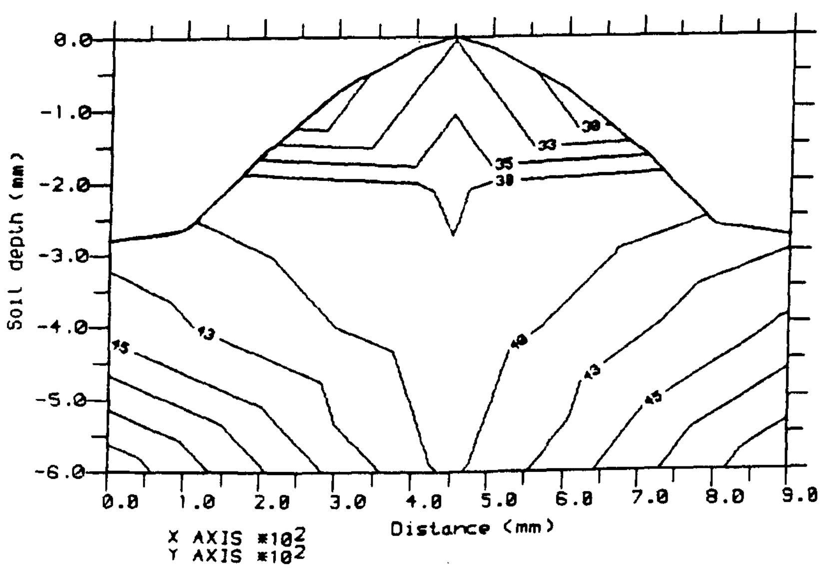


Figure 5 Soil moisture content distribution for tied furrow before fourth irrigation.
Application rate = 500 mm/hr

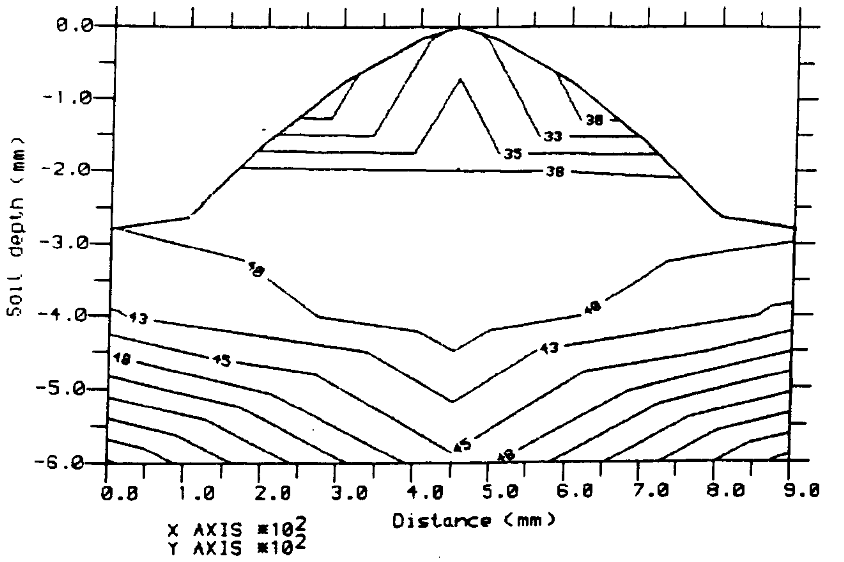


Figure 6 Soil moisture content distribution for tied furrow after fourth irrigation.
Application rate = 500 mm/hr

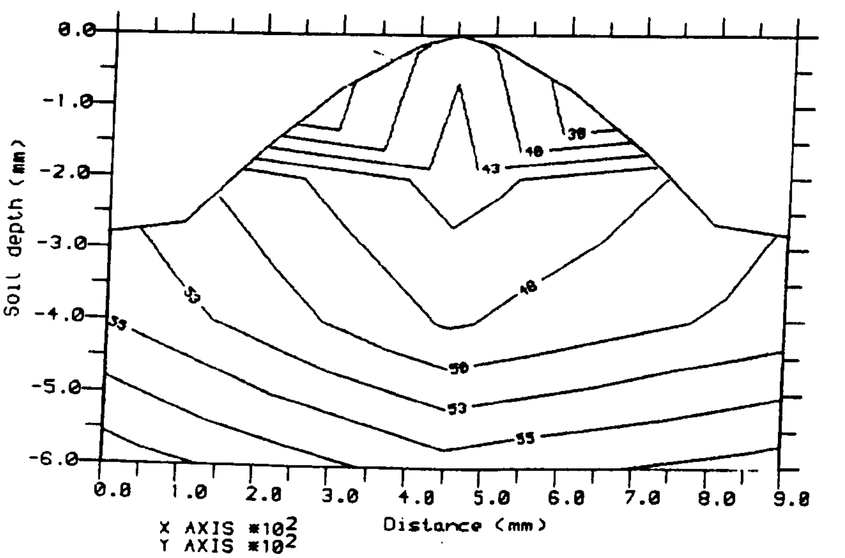


Figure 7 Soil moisture content distribution for free furrow before fourth irrigation.
Application rate = 100 mm/hr

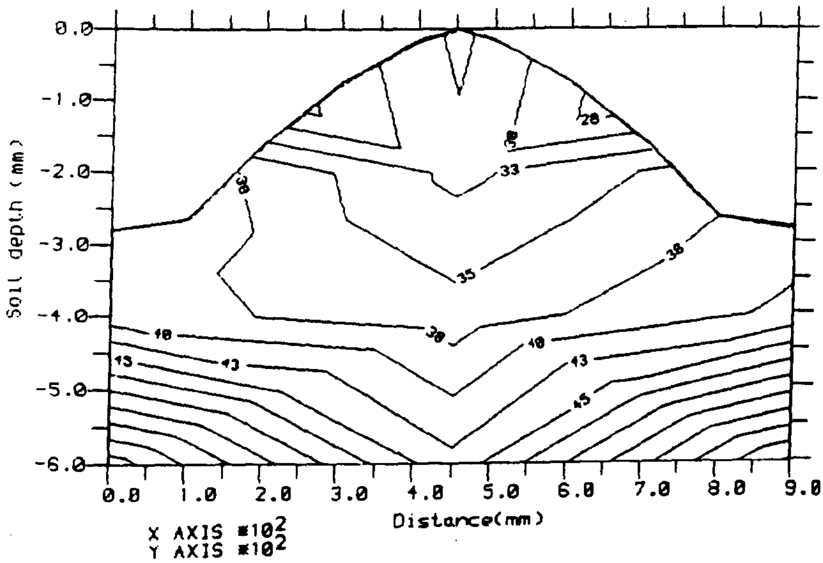


Figure 8 Soil moisture content distribution for free furrow after fourth irrigation.
Application rate = 100 mm/hr

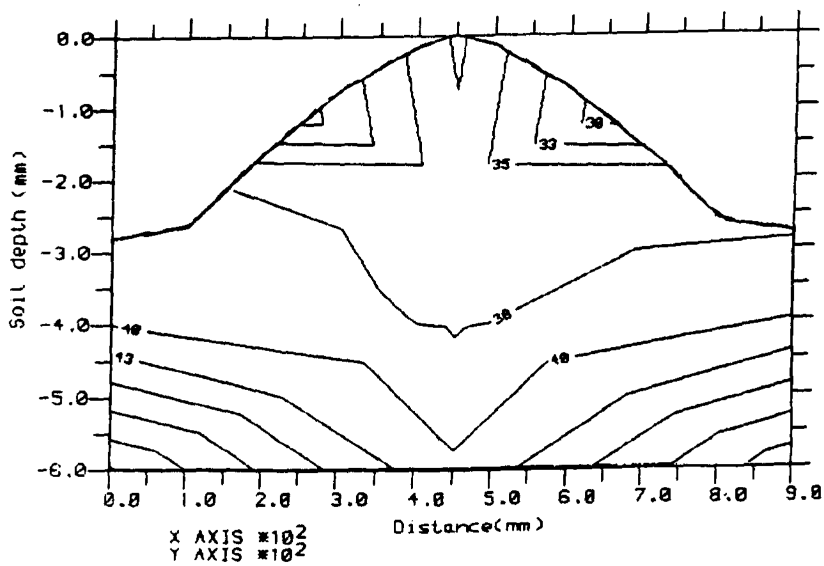


Figure 9 Soil moisture content distribution for free furrow before fourth irrigation.
Application rate = 300 mm/hr

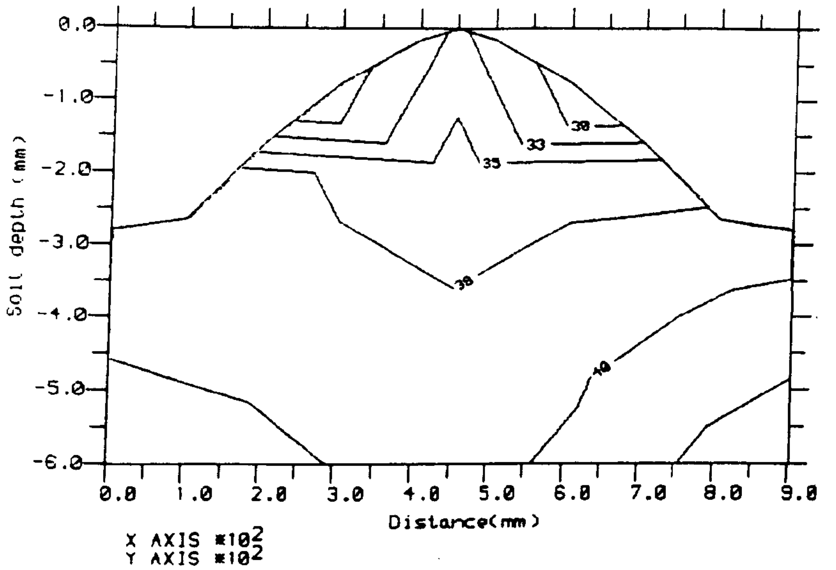


Figure 10 Soil moisture content distribution for free furrow after fourth irrigation.
Application rate = 300 mm/hr

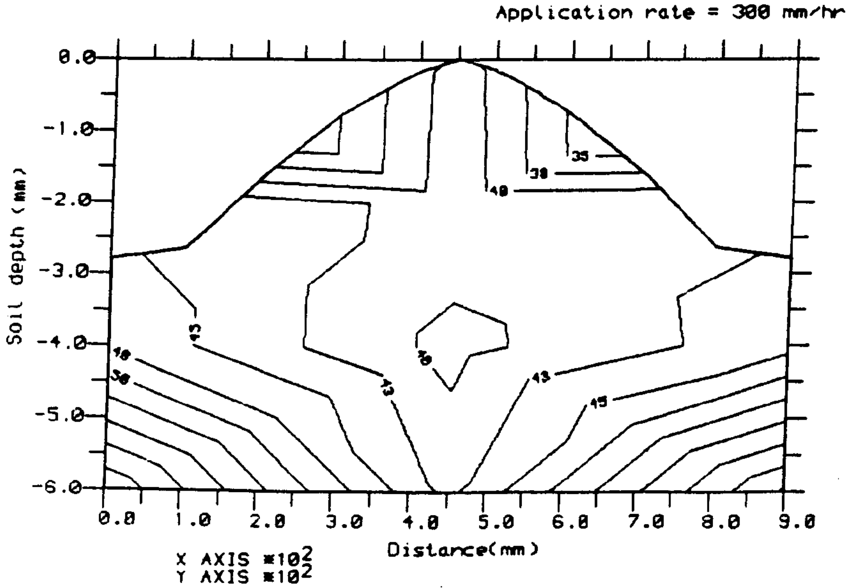


Figure 11 Soil moisture content distribution for free furrow before fourth irrigation.
Application rate = 500 mm/hr

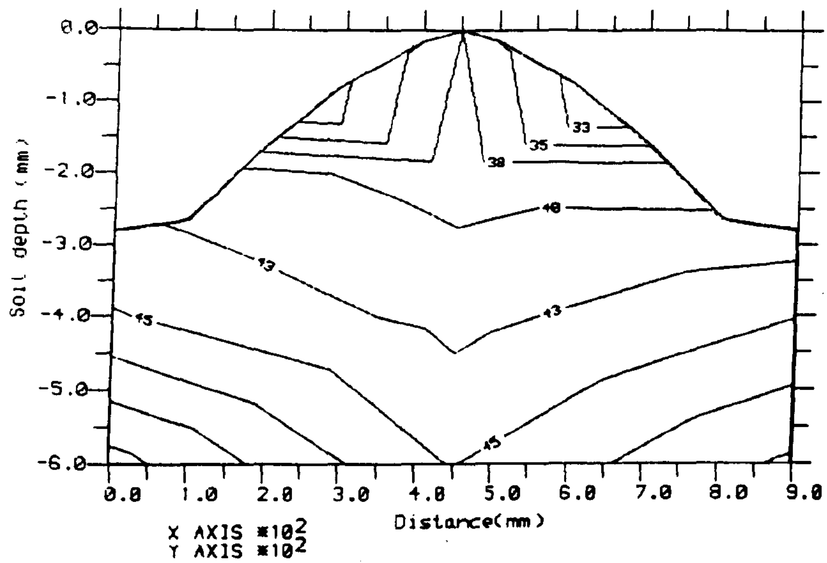


Figure 12 Soil moisture content distribution for free furrow after fourth irrigation.
Application rate = 500 mm/hr

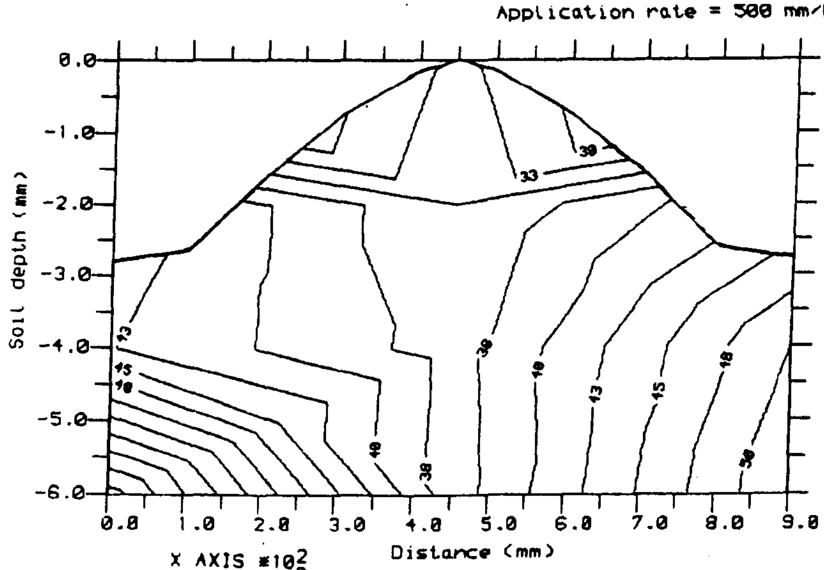


Figure 13 Soil moisture content distribution for raised bed before fourth irrigation.

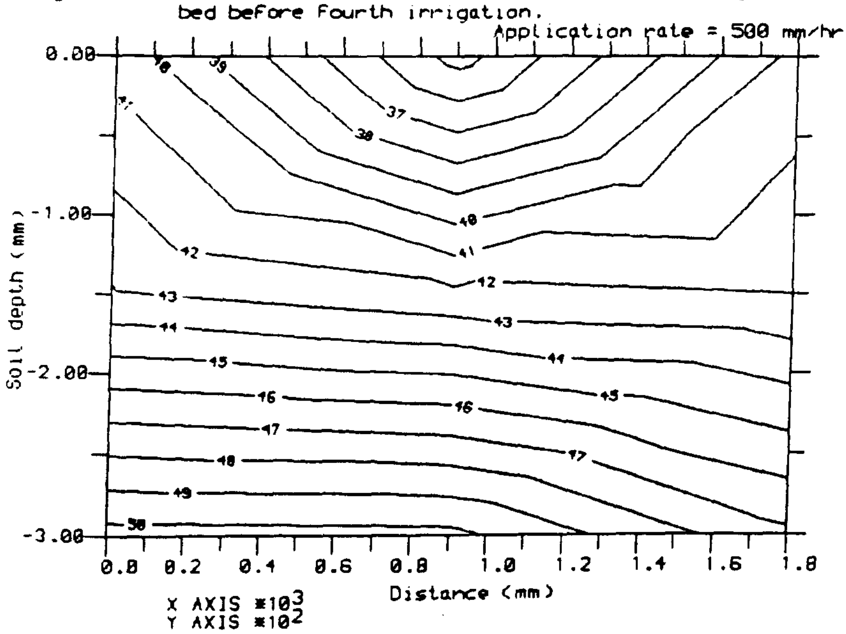


Figure 14 Soil moisture content distribution for raised bed after fourth irrigation.

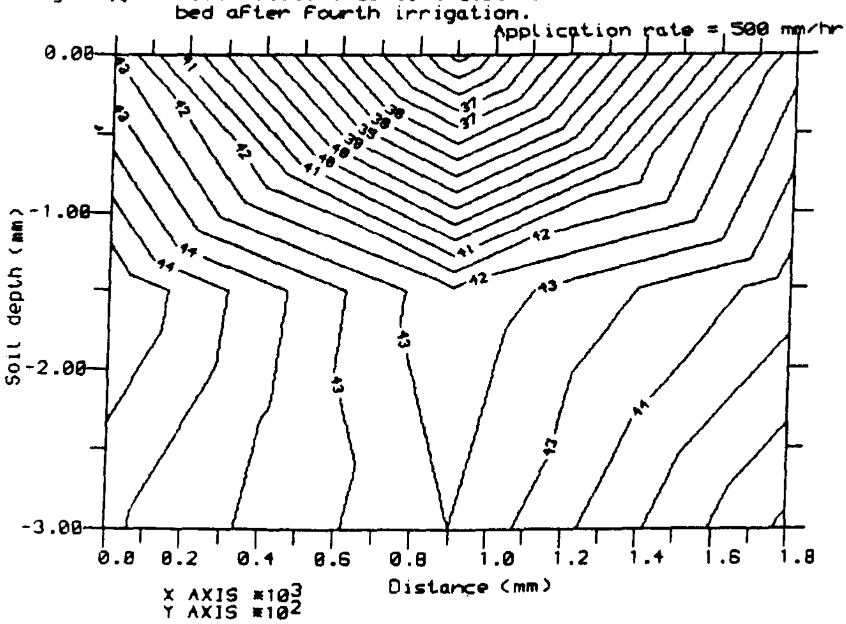


Figure 15 Soil moisture content distribution for raised bed before fourth irrigation.

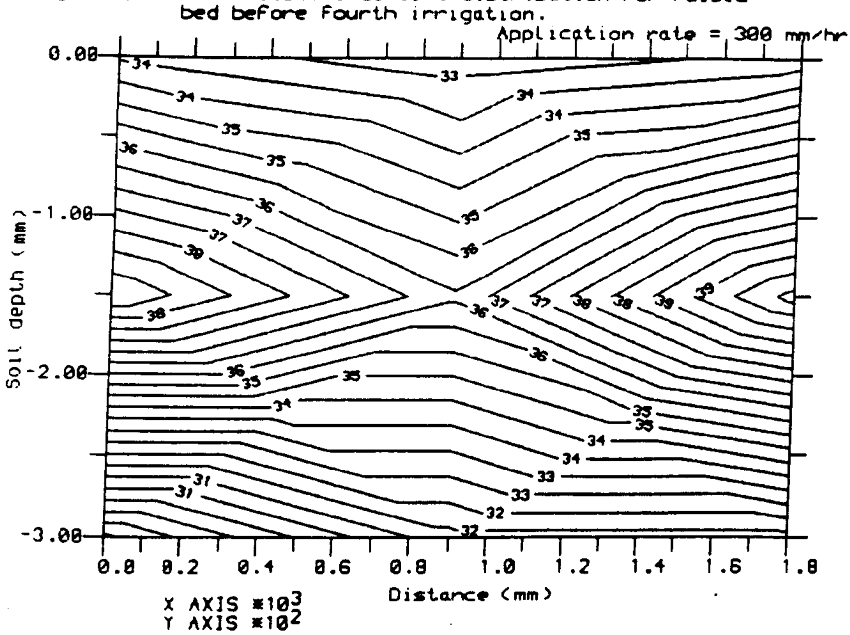


Figure 16 Soil moisture content distribution for raised bed after fourth irrigation.

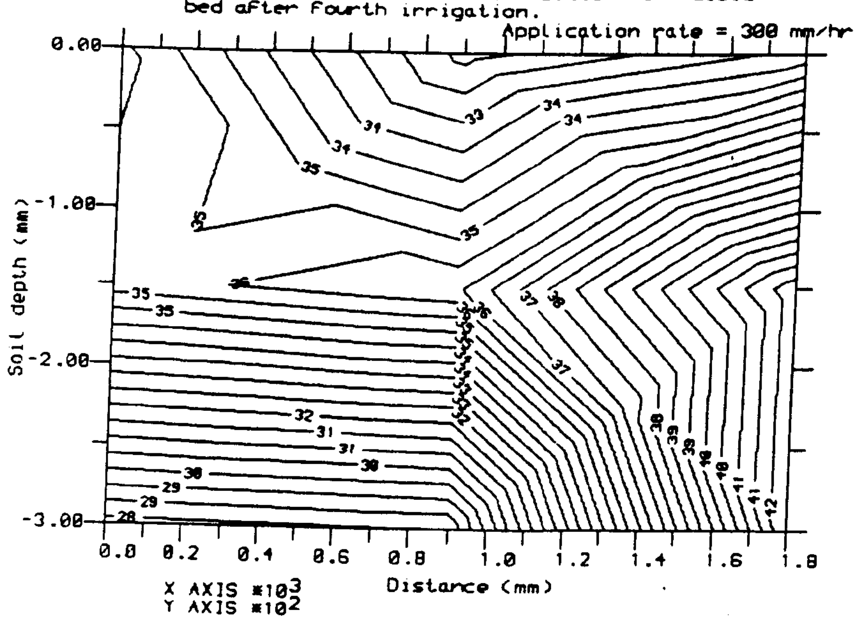


Figure 17   Soil moisture content distribution for raised bed before Fourth irrigation.

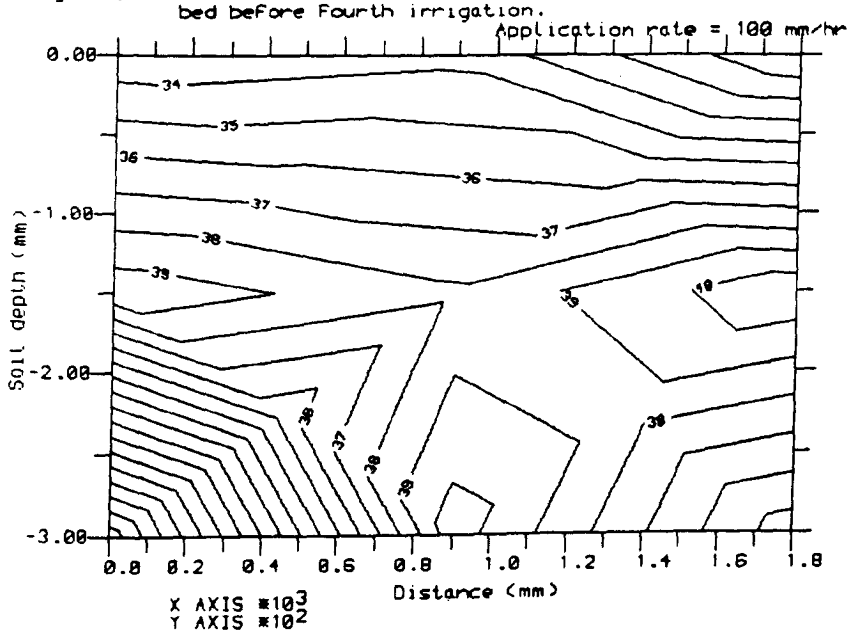
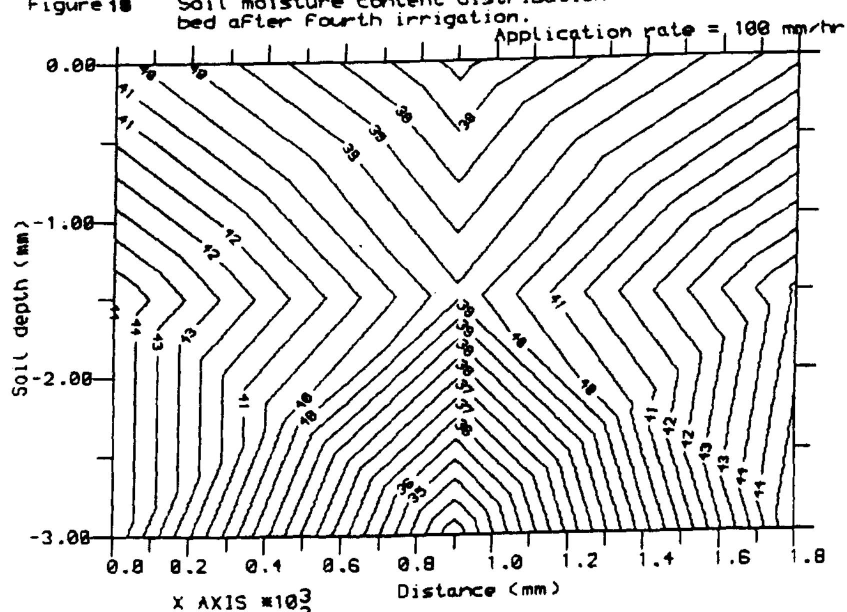
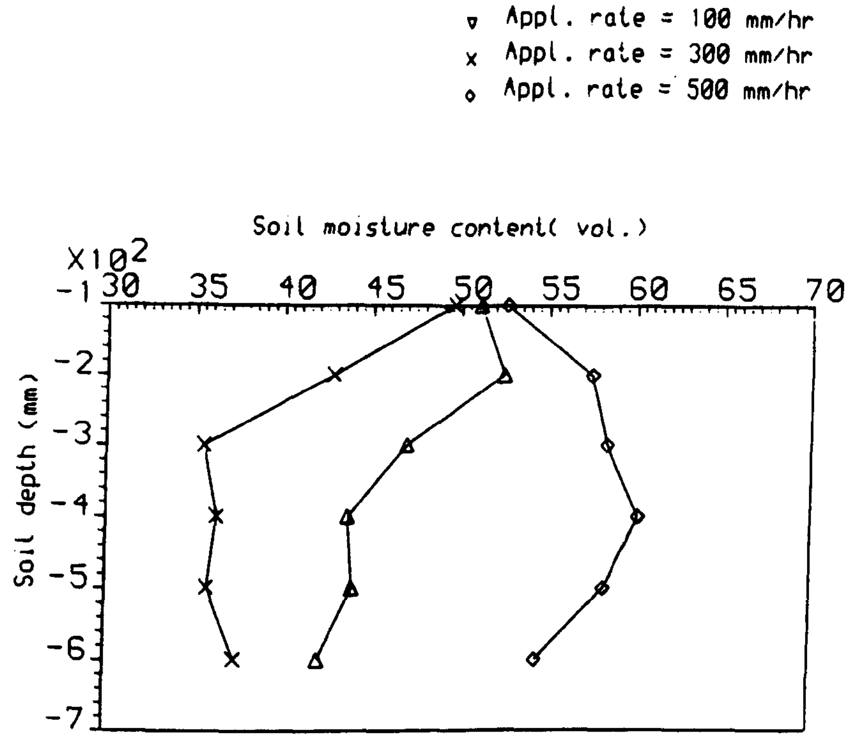
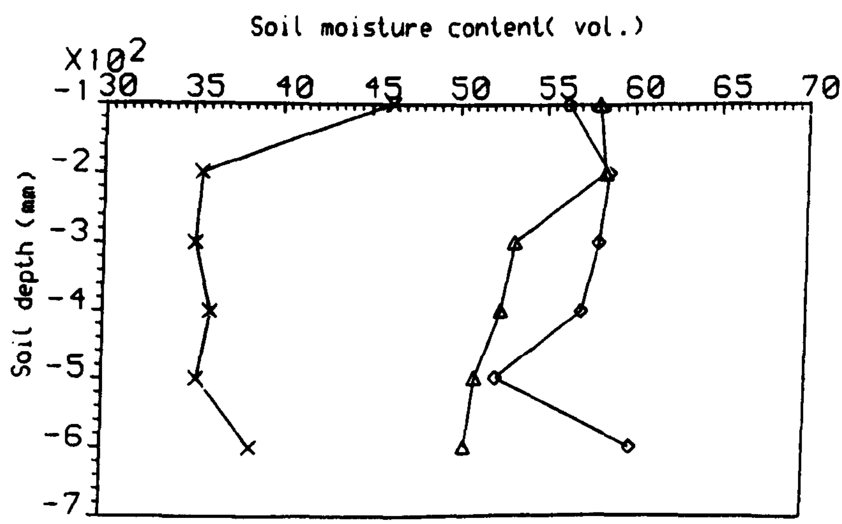


Figure 18   Soil moisture content distribution for raised bed after Fourth irrigation.





Before irrigation

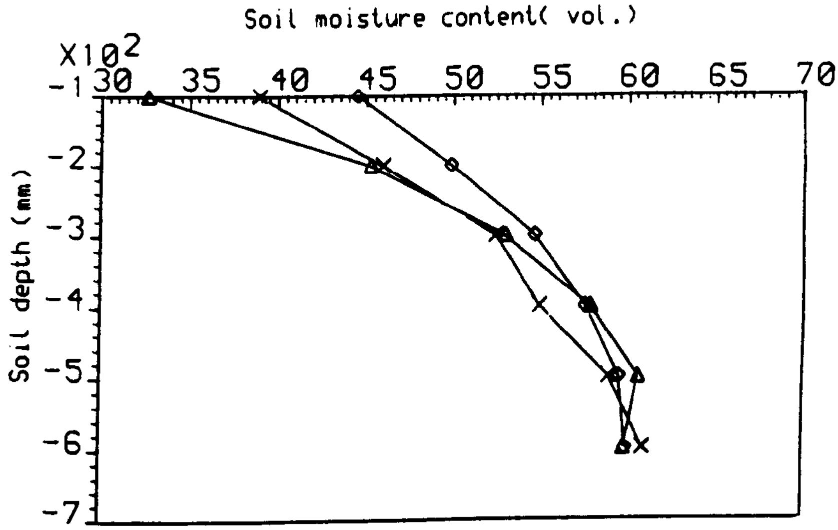


After irrigation

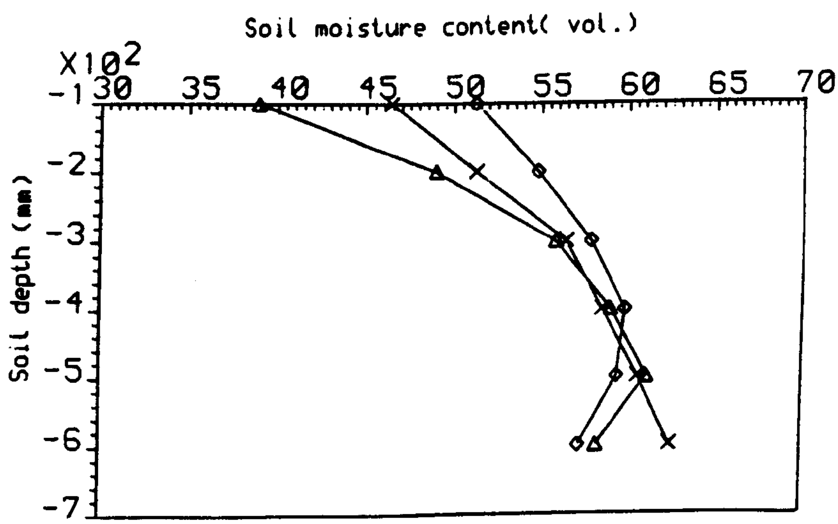
Soil moisture contents measured by neutron probe for raised bed.

APPENDIX A.3 (Continued)

▿ Appl. rate = 100 mm/hr
x Appl. rate = 300 mm/hr
◇ Appl. rate = 500 mm/hr



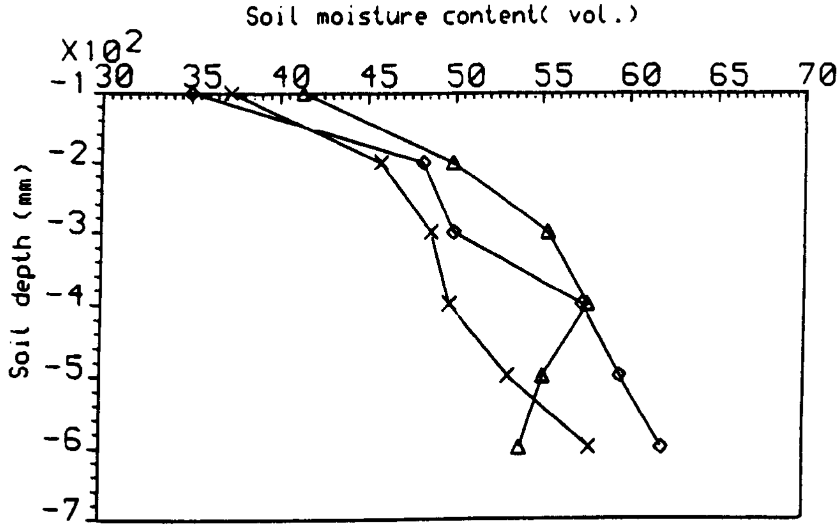
Before irrigation



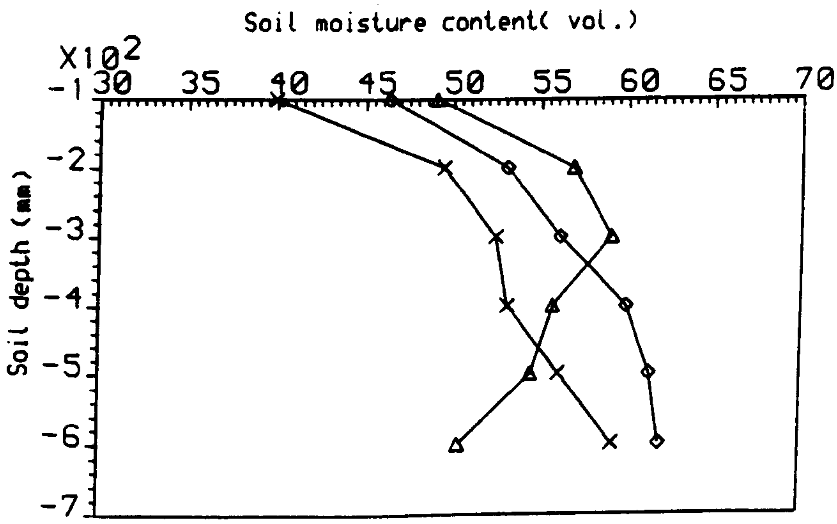
After irrigation

Soil moisture contents measured by neutron probe for free furrow.

▽ Appl. rate = 100 mm/hr
x Appl. rate = 300 mm/hr
◇ Appl. rate = 500 mm/hr



Before irrigation



After irrigation

Soil moisture contents measured by neutron probe for tied furrow.

Appendix A.4

Irrigation Scheduling
Potato crop
Year:1985

Soil water balance sheet

Date (day and month	Rainfall (mm)	Irrigation (mm)	S.M.D. (mm)
1/5/1985	0.0	0.0	16.0
2/5	0.0	0.0	17.9
3/5	0.0	0.0	18.9
4/5	0.3	0.0	19.7
5/5	0.8	0.0	21.1
6/5	0.0	0.0	22.5
7/5	0.0	0.0	23.7
8/5	1.2	0.0	23.8
9/5	0.0	0.0	24.6
10/5	0.0	0.0	25.1
11/5	0.0	0.0	25.6
12/5	6.3	0.0	20.7
13/5	0.3	0.0	21.1
14/5	11.7	0.0	10.3
15/5	0.0	0.0	10.8
16/5	0.0	0.0	11.4
17/5	0.0	0.0	11.9
18/5	1.5	0.0	12.5
19/5	0.4	0.0	12.7
20/5	11.2	0.0	2.6
21/5	4.1	0.0	0.0
22/5	0.0	0.0	1.1
23/5	0.0	0.0	2.7
24/5	0.6	0.0	4.1
25/5	1.1	0.0	5.2
26/5	4.3	0.0	2.7
27/5	4.9	0.0	0.0
28/5	0.0	0.0	1.6
29/5	0.0	0.0	4.0
30/5	0.0	0.0	7.0
31/5	0.0	0.0	9.2
1/6	0.0	0.0	11.0
2/6	0.0	0.0	12.5
3/6	0.0	0.0	14.4
4/6	7.7	0.0	8.3
5/6	6.3	0.0	3.2
6/6	19.9	0.0	0.0
7/6	0.0	0.0	1.0
8/6	0.0	0.0	3.2
9/5	0.0	0.0	5.3
10/6	0.2	0.0	7.0

continued Appendix A.4

Date (day and month)	Rainfall (mm)	Irrigation (mm)	S.M.D. (mm)
11/6	10.6	0.0	0.0
12/6	0.4	0.0	1.7
13/6	3.5	0.0	0.0
14/6	0.0	0.0	1.6
15/6	0.0	0.0	3.4
16/6	0.0	0.0	5.1
17/6	0.4	0.0	7.0
18/6	0.2	0.0	8.2
19/6	0.0	0.0	9.5
20/6	6.8	0.0	4.2
21/6	1.1	0.0	4.4
22/6	2.8	0.0	2.8
23/6	2.1	0.0	2.8
24/6	13.5	0.0	0.0
25/6	1.0	0.0	0.7
26/6	2.1	0.0	1.3
27/6	0.0	0.0	3.7
28/6	0.7	0.0	5.7
29/6	0.0	0.0	8.4
30/6	8.0	0.0	3.1
1/7	0.0	0.0	5.6
2/7	0.0	0.0	8.1
3/7	0.0	0.0	11.2
4/7	0.0	0.0	14.0
5/7	0.0	0.0	16.8
6/7	0.0	0.0	19.4
7/7	0.0	0.0	21.9
8/7	0.0	0.0	24.7
9/7	0.0	0.0	26.8
10/7	0.0	0.0	29.4
11/7	0.0	0.0	31.3
12/7	0.0	0.0	33.5
13/7	0.5	0.0	36.0
14/7	0.0	0.0	38.2
15/7	2.0	0.0	38.8
16/7	0.7	25.0	15.3
17/7	0.0	0.0	18.5
18/7	0.2	0.0	21.9
19/7	12.7	0.0	11.7
20/7	0.7	0.0	14.9
21/7	0.4	0.0	18.0
22/7	0.3	0.0	19.8
23/7	0.0	0.0	23.6
24/7	0.0	0.0	26.7
25/7	0.0	25.0	5.9
26/7	6.4	0.0	2.0
27/7	1.4	0.0	5.5
28/7	11.2	0.0	0.0

continued Appendix A.4

Date (day and month)	Rainfall (mm)	Irrigation (mm)	S.M.D. (mm)
29/7	8.3	0.0	0.0
30/7	0.0	0.0	2.1
31/7	1.5	0.0	3.9
1/8	0.0	0.0	7.4
2/8	4.6	0.0	5.4
3/8	0.3	0.0	10.1
4/8	6.6	0.0	6.5
5/8	0.0	0.0	10.1
6/8	2.4	0.0	11.4
7/8	1.0	0.0	13.0
8/8	1.3	0.0	15.7
9/8	0.0	0.0	18.5
10/8	0.0	0.0	22.0
11/8	0.7	0.0	24.6
12/8	3.7	0.0	26.1
13/8	0.0	0.0	28.8
14/8	0.0	0.0	31.2
15/8	0.0	0.0	34.3
16/8	3.0	0.0	34.6
17/8	0.2	25.0	12.4
18/8	1.8	0.0	12.2
19/8	7.2	0.0	8.1
20/8	0.5	0.0	10.3
21/8	3.5	0.0	10.7
22/8	0.0	0.0	13.4
23/8	2.6	0.0	15.3
24/8	0.0	0.0	18.5
25/8	0.5	0.0	21.7
26/8	0.0	0.0	24.5
27/8	0.0	0.0	27.5
28/8	0.0	25.0	5.4
29/8	0.0	0.0	9.0
30/8	0.0	0.0	13.0
31/8	0.0	0.0	16.4
1/9	0.0	0.0	20.2
2/9	8.2	0.0	15.0
3/9/1985	1.1	0.0	16.2