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**A Mathematical Model to Predict Surface
Runoff under Sprinkler Irrigation
Conditions**

Supervisor: Mr M Kay

June 1997

**This dissertation is submitted in fulfilment of requirement for the Degree of
Doctorate of Philosophy**



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ABSTRACT

A Mathematical Model to Predict Surface Runoff under Sprinkler Irrigation Conditions

By: Behzad Ghorbani

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Runoff from agricultural areas under sprinkler irrigation systems is a big problem. This is because runoff not only reduces water use efficiency (WUE), but also reduces soil fertility through depletion of fertilisers and pesticides, causes non uniformity of soil water content along the field slopes and ultimately reduces crop production and causes environmental pollution.

Although sprinkler irrigation systems are usually designed so that the water application rate is less than the soil infiltration rate to avoid runoff, there are a growing number of sprinkler systems where runoff has become a serious problem. Large mobile single sprinklers (rainguns) which can irrigate large areas in a relatively short time are prone to severe runoff problems, because of the high application rates. Modern centre pivot and linear systems, which have now been designed to run at low energy saving pressures also produce high application rates and potential runoff. Most runoff problems are dealt with in the field on a trial and error basis. Being able to predict runoff under sprinkler irrigation would enable water application rate to be recommended and cultivation practices to be 'designed' rather than guessed on a trial and error basis in order to store surface water and avoid runoff.

The objective of this study was to develop a mathematical model that can predict surface runoff from a small watershed area using sprinkler irrigation systems in either a stationary or moving condition. The objective was met in two ways: a mathematical model was developed from first principles called Overland Flow (OLF) and an existing model, KINEROS modified to EUROSEM, but designed for overland flow and soil erosion from hydrological

watersheds was adapted to suit micro-catchment conditions for both stationary and moving sprinklers. Both models are based on kinematic wave theory.

Both models were validated by laboratory and field experiments using stationary and moving sprinklers on simple plane and ridge and furrow cultivation practices. The validation results showed that the model predicts well the shape of the runoff hydrograph but also the key points for practical application. For example, time to start runoff, time to peak, peak flow rate, volume of runoff and time to end which are important when designing a cultivation practice in the field. The performance of the EUROSEM-KINEROS model was further evaluated by statistical techniques. There was good agreement between observed and model results.

The EUROSEM-KINEROS model was also used to examine the best practical techniques to minimise the surface runoff. The application of this model to sprinkler irrigation design and management was also assessed. The evaluation results showed that the hydrograph parameters can be used to recommend water application rate, water application time and / or to design soil and water conservation structures to avoid critical situation in the field.

Model validation for a moving sprinkler is recommended to be undertaken for different moving irrigators such as ranguns, centre pivot, side move systems and low energy precision application (LEPA) systems. Further investigations are also required to evaluate the use of the model to predict the effects of soil and water conservation techniques on runoff prevention for a cultivated land for different crops.

DEDICATION

to

Justice

“We sent aforime our messengers with clear signs and sent down
with them the **BOOK** and the **BALANCE** (of right and wrong) that
men may stand forth in **JUSTICE**”,
Qoran, Chapter Alhadid

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TABLE OF SYMBOLS

Symbol	Description	Dimension
$\bar{x}$	average of observed values	
ν	kinematic viscosity	m^2/s
α	hydraulic roughness	
ϕ	soil porosity	fraction
$\partial A/\partial t$	rate of cross sectional area with time	m^2/s
ϕ_m	matric flux potential	m^2/sec
α_s	hydraulic roughness of upper element	
Δt	time increment	s
$\partial V/\partial x$	rate of flow velocity along the slope	$\text{m}/\text{h}/\text{m}$
Δx	distance increment	m
a	infiltration coefficient (at^b)	
a_m	cross section of manometer	cm^2
A_c	cross section of soil cylinder,	cm^2
A	flow cross sectional area	m^2
A, B, P and p'	terms in kinematic wave equation	
ASR	roughness ratio across the slope	fraction
b	infiltration coefficient (at^b)	
B	saturated deficit of soil	mm
c	crop residue cover	fraction
$C, U.$	uniformity coefficient	%
C_o	runoff coefficient	%
d_d	raindrop diameter	mm
E_{kt}	total kinetic energy	N m
d_i	rainfall already absorbed into soil	
d_c	diameter of crop residue	mm
d	gross depth of water application	mm

$\Delta\theta$	variation of soil water content	
Ψ	matric potential.	mm
D_{50}	mean particle diameter of bed materials	mm
D_{65}	diameter of the bed material, 65 % is smaller	mm
D_a	difference between the number of measurement below and above M_a	
d_a	rainfall already absorbed into the soil	mm
D_b	difference between the number of measurement below and above M_b	
DH_p	difference of matric potential between two points	mm
d_r	runoff depth	mm
ds/dt	change in the depression storage with time	mm/h
E_k	kinetic energy	N m
$f(r)$	function of rainfall	
F_0	Froud number at the end of plane	
F^2	sum of square of errors	
f_d	friction factor for Darcy Weisbach equation	
F_o^2	sum of squares of deviations from mean observed data	
G	capillary drive	mm
g	gravity acceleration	m/s ^{1/2}
h	equivalent normal water depth	mm
H_0	pressure head at soil surface	mm
$h1$ and $h2$	heads of water at times t_1 and t_2	mm
h_1, h_2, h_3 and h_4	depth of overland flow at grids 1, 2, 3 and 4	mm
h_f	air entry value of soil water pressure	mm

H_f	pressure head at wetting front	mm
h_s	water depths of upper element	mm
i	instantaneous infiltration rate	mm/h
I	accumulated infiltration	mm
i_c	infiltration capacity	mm/h
k	dimensionless number	
$K(\Psi)$	unsaturated hydraulic conductivity	mm/h
k_o	value without raindrop impact	
K_{sat}	saturated hydraulic conductivity	mm/hr
$\bar{q}_o$	mean of observed	mm/h
L	length of stream	m
L_c	length of soil sample	m
L_f	distance between two points	cm
m	flow regim constant	
μ	dynamic viscosity	kg/m.s
m'	coefficient of area	
M_a	mean value above total mean value	mm
M_b	mean value below total mean value	mm
m_i	masses of raindrops	g
n	Manning coefficient	$m^{1/6}$
N	number of data points	
n_{stone}	Manning roughness correction for rock fragments	m^{16}
N_a	number of measurements above total mean value	
N_b	number of measurements below total mean	
p	pressure	bar
Q	runoff flow rate	mm/h
q	discharge per unit width	m^2/h

Q_b	lateral flow from bed	mm/h
Q_{bt}	total lateral flow to the bed from excess rainfall and upper element and sides	mm/h
Q_e	excess rainfall	mm/h
ϕ_i	initial soil water content	
Q_n	nozzle discharge	m ³ /h
q_o	observed runoff	mm/h
q_p	predicted runoff	mm/h
q_s	runoff rates of upper element	m ² /h
q_{sd}	runoff discharge from the sides	m ³ /h
q_{bd}	runoff discharge to the bed	m ³ /h
Q_s	lateral flow from sides	mm/h
Q_t	total lateral flow	mm/h
R	rainfall rate / water application rate	mm/h
ρ	water density	kg / m ³
R	rainfall intensity	mm/h
R_1, R_2	rainfall intensity at time 1 and 2	mm/h
R^2	model efficiency	
R_n	Reynolds number	
R_{nc}	critical Reynold's number	
R_c	percentage of rock fragment cover	fraction
S	longitudinal slope	
s	standard deviation	
s_s	soil sorptivity	m ² /h
S_b	bed slope	%
S_f	energy slope	m/m
S_i	initial relative saturation	fraction
S_{max}	maximum relative saturation	fraction
S_s	furrow side slopes	%
t	time	s
T_a	sum of the measurement above Ma	mm

T_b	sum of measurement below Mb	mm
t_c	time of concentration	min
t_p	time to ponding	s
t_{sur}	estimated time for runoff flow to reach channel	min
V	velocity	m/h
v_i	velocities of raindrops	m/h
V_v	volume	cm ³
W	widths of lower element	m
w	towpath spacing	m
W_s	water width of upper element	m
X	actual distance	m
X_i	observed depth of water	mm
$X_{opt.}$	optimised value	
Y	straight distance	m
y	maximum surface storage	mm
Z	inverse of slope	

TABLE OF ACRONYMS

TABLE OF ACRONYMS

Abbreviation	Description
<i>ANSWERS</i>	Areal Non-Point Source Pollution Systems Model
<i>CREAM</i>	Chemical Runoff and Erosion from Agricultural Management Systems
<i>ESP</i>	exchangeable sodium percentage
<i>EUROSEM</i>	European Soil Erosion Model
<i>F</i>	implicit function
<i>KINEROS</i>	Kinematic Runoff and Erosion Model
<i>LEPA</i>	Low-Energy, Precision Application systems
<i>OLF</i>	Overland Flow Model
<i>PAM</i>	polyacrylamid polymer
<i>PS</i>	polysaccharide polymer
<i>RECS</i>	recession factor
<i>RFR</i>	roughness ratio along the slope
<i>RMSE</i>	root mean-squared-error
<i>RUSLE</i>	Revised Universal Soil Loss Equation
<i>SROFF</i>	Surface Runoff Model
<i>USLE</i>	Universal Soil Loss Equation
<i>WUE</i>	Water use efficiency
<i>IAR</i>	instantaneous application rate
<i>ISO</i>	International Standard Organization
<i>SAR</i>	sodium absorption ratio

CHAPTER 1

INTRODUCTION

1. Introduction

1.1 Background

The dramatic growth of the population in the world increases the demand for food every day. Although nowadays economic/political constraints are more responsible for famine and solving the world food problems, to prepare sufficient food for this huge population needs both expanding the current cultivated area and producing crops more efficiently per unit area. To meet this purpose is necessary to irrigate the lands in parts of the world which are arid or semiarid regions. However, the shortage of water in many parts of the world is a serious problem, a limiting factor in expanding the agricultural lands and an agent preventing growth and development.

Low water use efficiency (WUE) intensifies the problem of lack of water. This can be reduced effectively by saving water through reducing losses. There are many reasons for saving water through improving WUE, for instance, to irrigate a larger area, reduce competition for water between users, reduce harmful effects of rising ground water tables, reduce the construction and maintenance costs, reduce nitrogen leaching, allow alternative uses of the water and change to higher added value crops.

WUE is concerned with the major losses such as runoff, spray due to evaporation and wind drift and deep percolation. Figure 1 demonstrates a conceptual model of the factors that influence water use efficiency. This study particularly is concerned with runoff under overhead irrigation. This is because overhead irrigation systems can increase WUE considerably to conquer the lack of water in many parts of world, if they are designed properly.

Runoff not only affects WUE, but also reduces soil fertility through depletion of fertilisers and pesticides, causes non uniformity of soil

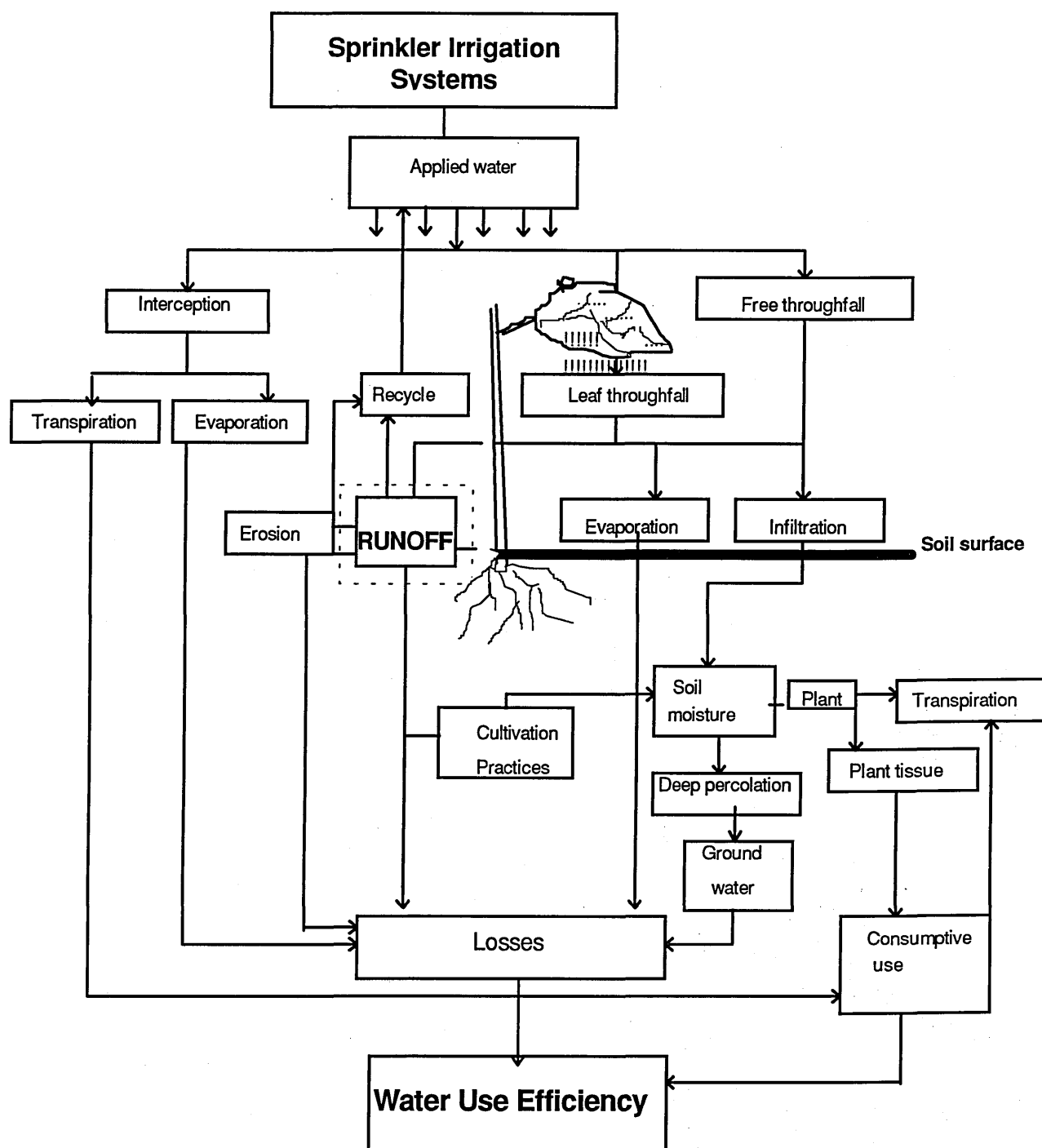


Figure 1.1 Conceptual model of factors affecting Water Use Efficiency

water content along field slopes and ultimately reduces crop production (Letely et al 1984, Ben-Hur 1994 and Ben-Hur et al 1995). Environmental pollution nowadays is a serious problem which is affected by runoff and soil erosion (Morgan et al 1992).

Although sprinkler systems are usually designed so that the water application rate is less than the soil infiltration rate to avoid runoff, there are a growing number of sprinkler systems where runoff has become a serious problem. Large mobile single sprinklers (rainguns) which can irrigate large areas in a relatively short time with low labour requirements are prone to severe runoff problems, because of the high application rates. Modern centre pivot and linear systems, which have now been designed to run at low energy saving pressures also produce high application rates and potential runoff.

Cultivation practices, normally used for soil and water conservation in high intensity rainfall areas, have been adapted to control runoff water under such irrigation systems. But much of the research work undertaken has been very site specific involving field cultivation trials, little attention has been given to developing a more fundamental understanding of the irrigation machine-water-soil system. This study describes the development of a fundamentally based mathematical model which can predict runoff on a range of soils, cultivation practices and water application regimes. The application of this model to sprinkler irrigation design and management is assessed and discussed in this dissertation.

1.2 Objectives

The objectives of this study can be summarised as follows:

1- To develop a model to predict surface runoff in a small watershed area under high water application rates such as occur when using a sprinkler or hose reel raingun irrigator in either stationary or moving condition,

2- To validate the model by measuring the runoff under different slopes, application rates and cultivation practices in field and laboratory experiments.

3- To use the model to examine the best practical techniques to minimise the surface runoff in order to increase water use efficiency.

CHAPTER 2

LITERATURE REVIEW

2. Literature Review

The purpose of this chapter is to review available literature on surface water runoff problems, factors that affect this process under sprinkler irrigation systems and mathematical models that are available to describe the process. The most appropriate approach to develop a model for predicting runoff is then decided.

2.1 Runoff problems

When the water application rate of any sprinkler irrigation systems exceeds soil infiltration capacity, the potential for surface runoff exists. The higher application rate associated with low pressure systems can exacerbate this problem. Among the irrigation methods, sprinkler irrigation, especially moving sprinkler irrigation systems (MSIS) such as centre-pivots have become increasingly popular over recent years in USA and many other countries (Ben-Hur 1994). The advantages of MSIS that makes it so popular are covering large areas, feasibility of operating on relatively rough field area and automation of the system. However, the majority of investigators reported that the MSIS have runoff problems. Because this system is designed to apply specific amounts of water in a short period, the instantaneous application rate can be high and so cause runoff and erosion. Pair (1968) reported that the maximum application rate under centre pivot machines often exceeds the infiltration capacity of soil. Otto (1989) reported that normal centre pivot application rates sometimes exceeds instantaneous infiltration rate and causes runoff. The magnitude of these problems depends on soil type, topography, cultivation practices and types of crop. The water application rate of MSIS with fixed spray nozzles can be more than 100mm/h, compared with about 10 mm/hr or less for fixed micro sprinklers or impact sprinkler heads (Ben-Hur 1994).

The surface runoff hazard is the greatest obstacle for low pressure sprinkler systems. Surface runoff reflects the interaction of the hydraulic characteristics of sprinkler, the soil-crop system and management practices. The impact of management is difficult to quantify but it is an important factor to consider. Several researchers have acknowledged the runoff problems with low pressure sprinkler systems. Gilley (1992) reported that energy costs, which are directly related to the operating pressure of the system, have caused the farmers to reduce the pressure of centre pivots. When the operating pressure is reduced, the wetting diameter is reduced as well. This results in high instantaneous application rates. High application rates associated with low pressure causes runoff on most of soils, except very permeable soils. The resulting runoff and erosion effects water application depth, crop yield and therefore, adversely affects crop production economics.

Kincaid et al (1969) reported a runoff of 22 % of water applied under high pressure sprinkler systems on a silty loam. Addink (1975) found values of runoff as high as 65 % of water applied under low pressure spray systems on a very fine sandy soil compared to 22 % under a high pressure sprinkler machine. They reported no runoff on a sandy soil for both high pressure and low pressure spray nozzles.

Letely et al (1984) and Ben-Hur et al (1995) reported that runoff can affect crop yield in three ways:

- 1- runoff from a cultivated field is lost for crop production,
- 2- surface runoff accelerates erosion, fertiliser and pesticide depletion,
- 3- accumulation of runoff in depression storage causes poor water distribution and reduces water efficiency and crop yield.

Low-energy, precision application (LEPA) systems have been developed to apply water to soil surfaces at very low pressure by using drop tubes or orifice - controlled emitters. LEPA systems, as illustrated by Gilley and Mielk (1980), apply water at much higher intensities and cause higher potential runoff than conventional centre-pivot. However, runoff from LEPA and other sprinkler systems can be reduced by providing sufficient storage on the soil surface using crop residue, depression storage and micro-basins.

The amount of surface runoff depends upon many factors, such as application rate, depth of applied water, initial soil water content, soil type and tillage practices. In this review the factors that can lead to an increase in runoff and erosion during irrigation, the effect of runoff on soil water distribution and the beneficial effect of soil and water conservation techniques to avoid runoff will be discussed. Among these are two main factors that determine the potential runoff. These are the application pattern of the irrigation system and the soil infiltration capacity (Ben-Hur 1994).

Although land slope may also influence runoff, studies are particularly devoted to soil erosion or the mechanics of runoff flow and relatively little research has been carried out to evaluate actual runoff particularly from irrigation. Therefore,, the effects of high application rates and steep slopes such as side slopes of ridges and furrows and their effect on runoff are lacking in the literature (Abo-Ghobar, 1988). Little research has also been undertaken to simulate or model the effect of cultivation practices on runoff even though cultivation practices are important to control runoff.

2.2 Water use efficiency (WUE)

Water use efficiency is defined in different ways by different specialists such as agronomists, physiologists (Huibers and Stroosnijder 1992) and economists (Van Vuren 1992). An engineering definition is the ratio between output and input values of water per system and this definition has been accepted by irrigation engineers and scheme managers (Van Vuren 1992). In other words, WUE is the ratio of water beneficially used to the amount of water delivered to the field (Israelsen and Hausen 1962). The engineering definition of WUE is therefore concerned with, the amount of water applied and the losses of water through runoff, evaporation and deep percolation (Figure 2.1). Water use efficiency is an important factor to consider in planning, designing, operating, maintaining and managing irrigation schemes in order to optimise energy and water (Van Vuren 1992; Yaxin and Guangnyun 1993).

Low water use efficiency associated with shortage of water has been one of the main limiting factors of development in many parts of the world. For example, Iran is a big country with the area of 165 million hectares (ha) and average annual precipitation of 224mm, only a quarter of world average precipitation. Unfortunately, the central part of Iran is an arid or a semi arid region where water shortage is a serious problem. The water use efficiency of this region is very low, about 40 per cent, i.e. approximately 60% of applied water is lost due to poor irrigation design and management. The proportions of water consumed in different sectors are urban services and industry 5%; and agriculture 95% (Fardad 1990). If the WUE in the agricultural sector could be improved, a lot of water could be saved for the expansion of agriculture and other purposes.

There are many reasons for saving water through improving WUE:

- 1- a wish to irrigate a larger area: i.e. the extension of schemes with efficient water will be achieved.
- 2- to reduce competition for water between users: Thus an increase in efficiency in head end reaches will result in saving water for tail end reaches.
- 3- to reduce harmful effects of rising ground water tables: overirrigation can cause rising water tables in the same or neighbouring areas. This may lead to waterlogging, salinization and increased drainage costs.
- 4- construction and maintenance saving: High water irrigation efficiency reduces the total amount of water which is needed and ultimately reduces the volume of reservoir and conveyance capacity.
- 5- reduction of leaching losses of fertilisers and pesticides
- 6- alternative uses of water: High irrigation efficiency can save water for other purposes.
- 7- changing towards high valued crops for example vegetables.

Occasionally, there are some good reasons for not increasing the WUE. This includes an unfavourable cost-benefit ratio, where water is not a scarce good, when excess water is used downstream, when there is a leaching requirement and other reasons such as labour cost (Van Vuren 1992).

Overall, irrigation strategies should be considered to maximise or optimise production, while minimising water losses, conserving water and preventing environmental pollution.

2.3 Runoff

When rainfall exceeds soil infiltration capacity runoff occurs. Wilson (1978) reported that although there is a relationship between runoff and rainfall, this is not a direct one. There are other factors such as evaporation, interception

storage, depression storage, infiltration and soil water content which must be considered. Furthermore, the rainfall, catchment size, slope and shape, altitude, surface and subsurface geology and climate should be involved as well. In spite of the foregoing it is possible to create an empirical relationship between annual runoff and precipitation. A simple correlation can be formulated as follows:

$$Q = aR + b \quad 2.1$$

Where Q = runoff flow rate, R = rainfall rate, a and b are coefficients . Several investigators reported that runoff will not happen until the soil surface depression fills. Oliveira (1987) illustrated that when the rainfall intensity or water application rate is more than the instantaneous infiltration rate runoff occurs after the soil surface storage fills (usually in the range 2 to 5 mm). Hortonian overland flow starts when the rainfall rate exceeds the infiltration capacity and sufficient water ponds on the surface storage (Woolhiser et al, 1990). According to Huibers and Stroosnijder (1992) when there is high rainfall intensity, runoff occurs after satisfying infiltration and soil surface storage (2-5 mm). In general, overland flow is a function of velocity (V) and flow depth (h), i.e.

$$q = f(V, h) \quad 2.2$$

Velocity depends on slope angle and roughness. It also relates to the type of flow which can be laminar or turbulent. In practice, natural roughness and rainfall drop impact cause turbulent flow which has the equation

$$q = \alpha h^m \quad 2.3$$

Where, q = discharge per unit width, a = coefficient describing bed roughness and slope, m = coefficient describing flow regime and h = the depth of runoff. As illustrated by Weyman (1975), flow rarely forms a true sheet under the natural condition, since depressions hasten the local concentration of water into rills. In a rill the depth and velocity increases rapidly. The discharge per unit width can be assessed for a wide plane or channel from the Manning formula

$$q = \left(\frac{1}{n}\right)h^{5/3} \times S^{1/2} \quad 2.4$$

Where, n = the roughness coefficient, S = the longitudinal slope of the water surface and h = the depth of water. Downstream increases in discharge are the result of continuous inflow of water from overland flow and direct channel precipitation.

Surface runoff over a catchment is known to follow certain laws of physics such as conservation of mass (continuity) and momentum. Overland flow on a micro-scale is a complicated three dimensional flow. However at a larger scale it can be viewed as a one dimensional process in which flow rate is a function of flow depth (equation 2.3). This equation is used in conjunction with the continuity equation as follows (Woolhiser et al, 1990)

$$\frac{\partial q}{\partial t} + \frac{\partial h}{\partial x} = Q(x, t) \quad 2.5$$

Where q = the flow rate per unit width of plane or channel, t = time, h = the depth of flow over the land, x = the longitudinal distance and Q = the surface runoff (Figure 2.1).

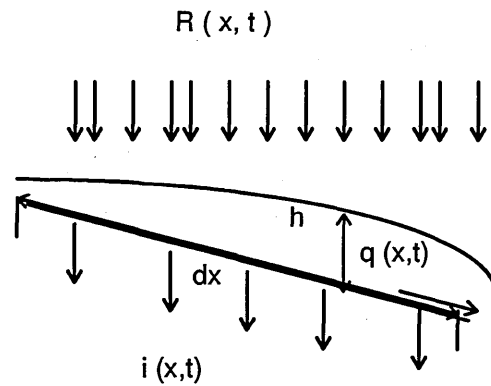


Figure 2.1 Runoff from a simple plane

2.3.1 Flow regime

The behaviour of flow is basically governed by the effect of viscosity and gravity relative to the inertia force of flow. If the viscous force is strong relative to the inertia force the flow regime is laminar. When the viscous force is weak relative to inertia force the flow regime called turbulent. There is a mixed state between laminar and turbulent called transitional flow. The relative effects of viscosity to inertia is shown by:

$$R_n = \frac{V \times h}{\nu} \quad 2.6$$

$$\nu = \frac{\mu}{\rho} \quad 2.7$$

Where R_n = Reynolds number, V = velocity of flow, h = the depth of flow, ν = the kinematic viscosity (m^2/s), μ = Dynamic viscosity ($\text{kg}/\text{m.s}$) and ρ = water density (kg / m^3). An overland flow is laminar, if the R_n is smaller than the critical Reynolds number and turbulent if R_n is larger. As R_n increases the state of flow changes

from laminar to turbulent. Laminar flow conditions can be defined as follows (Chow 1956, Woolhiser et al 1990 and Danniell et al 1995)

$$k = \frac{8gSh^2}{v \times V} \quad 2.8$$

$$\alpha = \frac{8gS}{v} \quad 2.9$$

where α is friction factor, S = slope and V = average velocity. Darcy-Wiesbach function factor (f_d) can be stated as follows:

$$f_d = \frac{k}{R_n} \quad 2.10$$

Where k is a dimensionless parameter. It is 24 for uniform laminar flow in a rectangular channel. The height of surface roughness is quite important. The value of k increases as the roughness of the surface increases and it may reach 14,000 for a rough surface. The values of R_n are of the order of 500 for rough surfaces increasing to 1,000 or more for smooth surface (Langford 1975).

Unlike laminar flow, there is no theoretically derived velocity profile for turbulent flow. The following equation recommended by Blasius describes the turbulent flow over smooth surfaces which can be derived from velocity profiles (Langford, 1975):

$$\alpha R_n^{.25} = 0.223 \quad 2.11$$

Chow (1956) reported that there are three types of flow over rough surfaces. These are isolated roughness flow, wake-interference flow and quasi- smooth

flow. These three types of flow may all occur in a field. However, the ground surface of watersheds, especially agricultural areas are mostly concerned with the quasi-smooth. Since the depth of overland flow seems like a film of water and the roughness elements are placed close together so that flow skims the crest of elements. In this case grooves between the elements fill with dead water. Therefore,, the surface acts as hydraulically smooth. However, quasi-smooth flow has a higher friction factor than the flow over real smooth, because the grooves dissipate a certain amount of energy.

According to Danniell et al (1995) for a disturbed laminar flow, dimensional analysis shows that k could be related to bed roughness (D_{50}/h), raindrop diameter to flow depth (d_d/h) and ratio of rainfall rate to channel discharge (q_s / q)

$$k = F\left(\frac{d}{h}, \frac{q_s}{q}, \frac{D_{50}}{h}\right) \quad 2.12$$

$$k = f_d R_n \quad 2.13$$

Where d_d = raindrop diameter, D_{50} = mean particle diameter of bed materials, h = depth of flow, q = channel discharge and q_s = rainfall inflow rate. The changes in the slope of runoff hydrograph may indicate in flow regime (laminar or turbulent). Therefore,, curves that have more than one slope, flow starts from laminar and after a short time changes to turbulent flow (Abo-Ghobar 1988).

2.3.2 Peak flow rate

Peak flow runoff from a field together with critical duration of rainfall create a critical situation which should be avoided in sprinkler irrigation design and management. It is important to know when and how this situation occurs in agricultural areas when sprinkler systems are running. Several researchers such

as Betson (1964), Larson and Mechmeier (1968), Stephenson and Meadows (1986), Meynink (1976) and Chen et al (1993) found that only a fraction of the catchment area was usually contributing to the peak runoff rate. They also found that the critical duration of rainfall that caused the maximum peak discharge could be shorter than the time of concentration. Knowing the time of concentration the critical rainfall duration can be found to avoid the peak runoff that occurs after applying sprinkler irrigation for a period as long as the time of concentration.

Time of concentration can be defined as the time required for a particle of water to move from the most hydraulically distant point of the basin to the outlet (Donald 1970). Several investigators such as Kirpitch (1940), Chen and Wong (1990) and Fetter (1994) reported different methods to determine the time of concentration. Among them the following formula was reported by Fetter (1994)

$$t_c = \frac{L}{V} + t_{sur} \quad 2.14$$

Where, t_c = the time of concentration, L = the length of stream, V = the velocity of water obtained from the Manning equation and t_{sur} = estimated time for runoff flow to reach channel.

2.4 Hydraulic roughness

Runoff flow velocity over a surface is affected by surface hydraulic roughness. This had been divided into grain and form roughness by Foster et al (1984). The grain roughness is the variation in surface elevation associated with grain scale. The grain scale is generally that of water stable aggregates or particles. The form roughness is the variation in surface elevation associated with the features of

larger than grain scale and smaller than hillslope. Gilley et al (1989) evaluated the relationship between soil texture on the grain roughness. They indicated that a larger grain roughness is associated with increasing clay content and decreasing silt content. Figure 2.2 shows a soil textural triangle (USDA) indicating values of $KS^{0.5}$ decreasing with rougher surfaces. Where k is the term including hydraulic roughness (c , Chezy coefficient) and bed slope (S) and shaded region is the range of textures from which the relationship was derived.

The Manning roughness coefficient has been used to describe the grain roughness that is important as an input parameter in predicting overland flow in several hydrological models such as KINEROS (Woolhiser et al, 1990) and EUROSEM (Morgan et al, 1993). Several methods have been reported in the literature for estimating the Manning roughness. For example, Strickler used the median particle size of bed material to estimate the Manning roughness as follows:

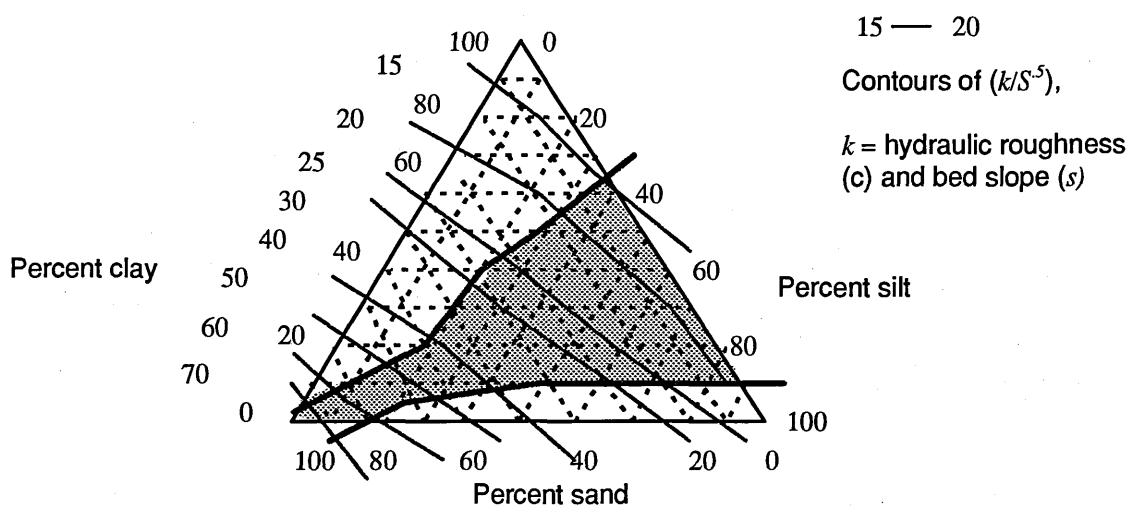


Figure 2.2 The soil textural triangle (After Gilley et al 1989).

$$n = 0.0342D^{1/6} \quad (\text{where } D \text{ is in English unit}) \quad 2.15$$

$$n = 0.047D^{1/6} \quad (\text{where } D \text{ is in metric unit}) \quad 2.16$$

D is the median diameter from the particle distribution of the soil. According to French (1985) there is significant disagreement between authors concerning the value of the coefficient in equations (2.15 and 2.16). For example Henderson suggested 0.034 in m units, Raudkivi gave 0.042 as m units where D_{65} is the diameter of the bed material such that 65 % is smaller, Garde and Raju suggested .039 and D_{50} in feet units, Subramanya gave 0.047 and D_{50} , Meyer-Peter and Muller suggested 0.038 and D_{90} and Ghorbani B (1988) gave 0.0315 and D_{75} in metre units.

Chow (1956) and French (1985) suggested the velocity method. Engmann (1986) determined Manning's n from the equilibrium hydrograph where the infiltration rate was constant under a rainfall simulator. Mohamoud (1992) determined the detention storage from hydrograph analysis and used the Manning equation to obtain Manning's n under different cultivation practices. According to Mwendera and Feyen (1992), since tilled soils are continuously changing due to rainfall and runoff, a method of updating Manning's coefficient may improve runoff flow from such soils. So they developed empirical formulae which relate Manning's coefficient to random roughness. Although there are several methods for estimating Manning's n , it is still difficult to determine a constant value precisely especially for an agricultural area under different cultivation practices.

The sensitivity analysis of hydrological models to hydraulic roughness by investigators determined how important this parameter was. For example, the sensitivity of models such as EUROSEM to the Manning coefficient depends upon the objectives of model. Quinton (1994) reported that hydrograph parameters are insensitive or low sensitive to the Manning coefficient. For

instance, time to peak and peak overland flow (which are important objectives in irrigation design) are respectively insensitive and low sensitive to the Manning coefficient. But Smith (1997, personal communication) reported that the hydraulic roughness is important for estimating peak flow runoff of short storms (Figure 2.3). Therefore,, if the amount of runoff which must go into storage changes it can have a significant effect on peak flow for short events. He also reported that the infiltration rate and roughness coefficient has an interaction effect on the shape of the rising limb of the runoff hydrograph, but later in a storm the effects of infiltration are significantly different from the effect of roughness (Figure 2.4). This is because the infiltration rate and roughness coefficient can affect the shape of the rising limb of hydrograph and the peak runoff for a short storm.

2.4.1 Form roughness

Further adjustments to Manning's n will be necessary to consider surface micro-topography or form roughness, involving vegetation and stoniness. As defined by Hairsine et al. (1992) micro-topography is the expression of soil structure at the soil-atmosphere interface when dry, or of the interface between the soil surface and water level when free water is ponded or is flowing over the soil surface. The role of micro-topography on runoff depends on shape characteristics or the morphology of surface. If the soil surface has 10 % or more cover of stones or rock fragments, the value of Manning's n should be corrected as following formula (Poesen 1992).

$$n_{stone} = ne^{.018R_{rc}} \quad 2.17$$

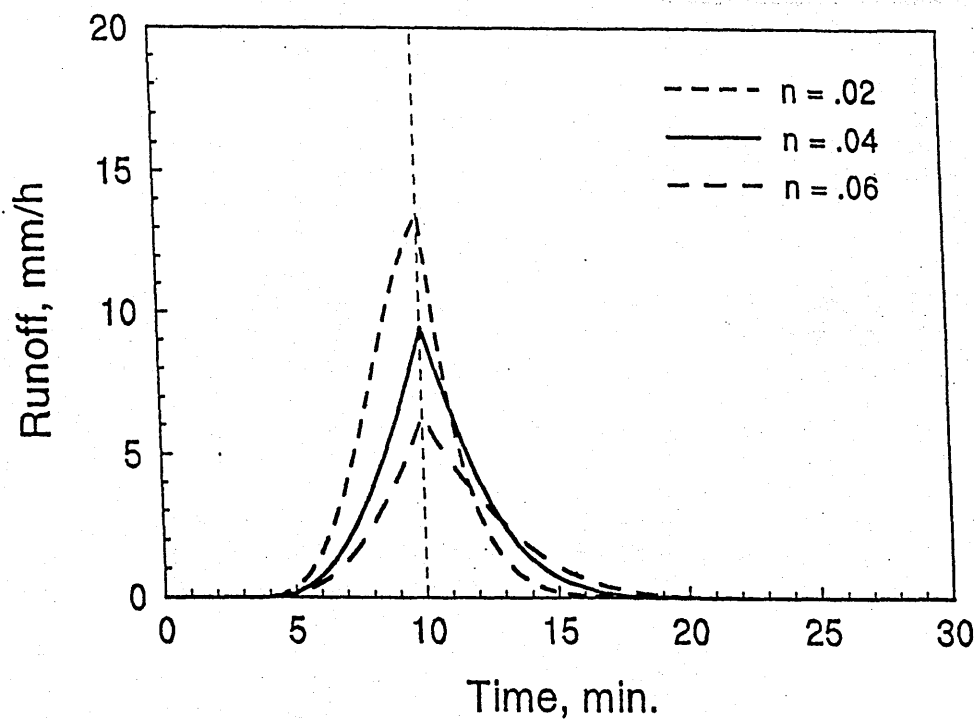


Figure 2.3 The effect of Manning's n for short storm (Smith, 1996, personal communication)

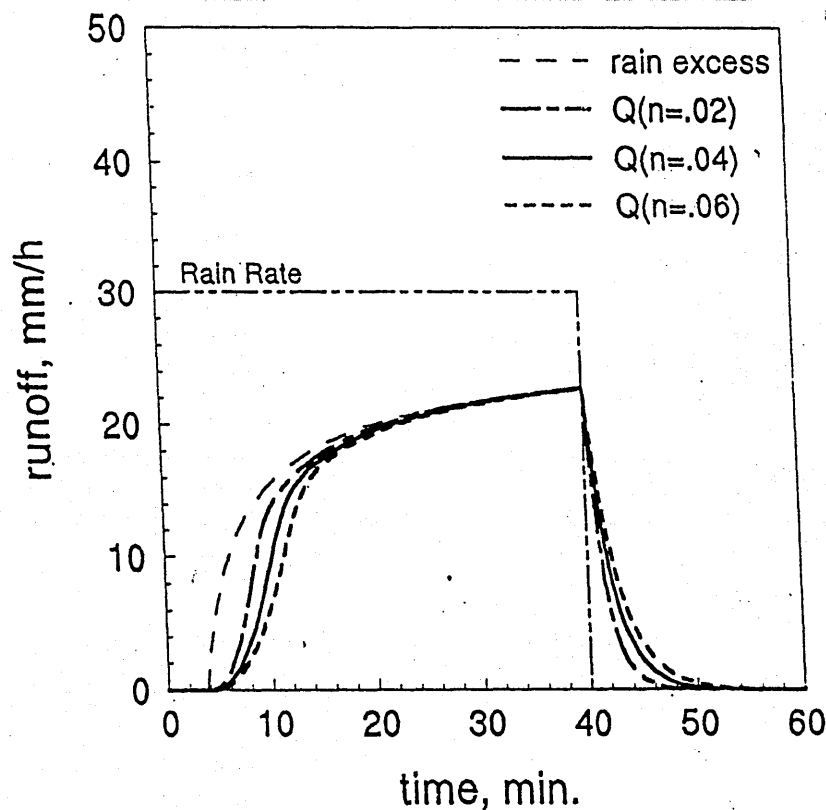


Figure 2.4 The effect of Manning's n in relation to surface storage (Smith, 1996, personal communication)

In which n_{stone} = the Manning roughness for a surface with rock fragments, n = the Manning coefficient without stone or the rock fragment and R_{rc} = the percentage of fragment cover (Morgan et al 1993). The percentage of stone can be determined by using the grid line method. In this method the area of squares in which the stones or the rock fragments are visible is divided by related total area under examination.

2.4.2 Depression storage

The most common quantification of the effect of surface roughness on runoff is the volume of water or the equivalent depth of water which can be stored in surface storage. It is assumed that this depression storage must be filled by excess rainfall prior to the beginning of runoff. However as described by Linsely et al (1988) runoff begins prior to maximum depression storage being filled. Figure 2.5 demonstrates the parts of depression storage which will be filled at different times. Storage (a) overflows before the other stores are filled. Storage (c) may overflow to fill (b) but not result in runoff until store (d) is filled.

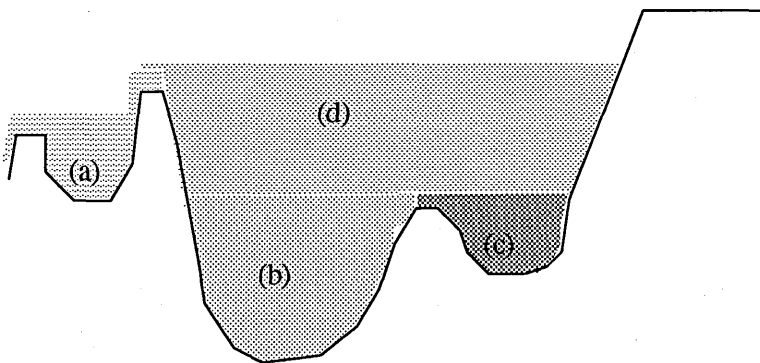


Figure 2.5 Depression storage

According to many researchers such as Gayle and Skaggs (1978) and Larson (1979) depression storage can be changed by the impact of water drops. The changes for clay loam and sandy loam ranged from 8 to less than 1 mm. They also found that for swelling clay soils it can approach 25 mm when the soil is cracked. Depression storage is an important factor but it is not included in most hydrological models. When looking at runoff from irrigated fields, depression storage can be important. However, this is described in two terms in the EUROSEM model (Morgan et al 1993), roughness ratio along the slope (*RFR*) and roughness ratio across the slope (*ASR*). These ratios are the proportion of difference between actual distance (*X*) and straight distance (*Y*) to actual distance between two points either along the slope or across the slope as follows (Figure 2.6):

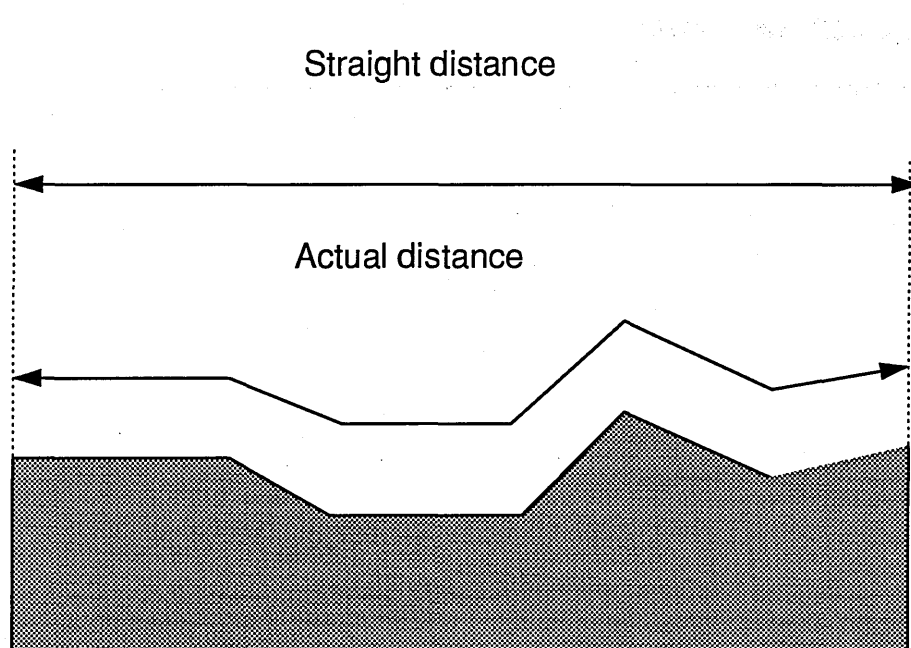


Figure 2.6 A definition sketch of roughness ratio

$$RFR(or(ASR)) = \frac{(X - Y)}{X} \times 100 \quad 2.18$$

The surface ratios are important inputs to the EUROSEM model, because they are used to describe the effects of different cultivation practices. In view of the variation in soil types it is preferable to use the measured not the recommended values as inputs in that model (Morgan et al 1993).

2.4.3 Rainfall intensity

According to Langford (1975) rainfall intensity can have an important effect on hydraulic roughness. However, for rainfall intensities greater than 13 mm/hr, the hydraulic roughness in fully turbulent flows was independent of rainfall intensities. He stated that the raindrops were the main source of turbulence and they have more effect at low R_n . At low R_n (<900), laminar flow is valid for smooth surfaces. However, the impact of raindrops may cause patches of turbulence even at low R_n .

Kisisel and Delleure (1973) found that there was an interaction between the bed roughness and rainfall intensity. The bed shear was increased by rainfall and it was greater for the rough surface than the smooth. For a laminar flow over a smooth surface the hydraulic roughness (k) is defined by the following equation which is a function of rainfall intensity :

$$k = 27.2 \times \left(\frac{R}{25.4} \right) \times 0.407 + 24 \quad R_n < 900 \quad 2.19$$

In which R = rainfall intensity (mm/hr). For R_n between 900 and 2,000 the flows were in a transitional state and the above equation could not be fitted to the data.

Danniel et al (1992) recommended $R_n < 500$ for laminar flow and for transition between 500 and 2000. Fully turbulent flows were described by

$$kR_n \times 0.25 = 0.262 \quad 2.20$$

The hydraulic roughness for turbulent flow over a smooth surface is essentially independent of rainfall intensity.

2.5 Infiltration

Infiltration rate is the rate at which water enters the soil. As the wetting time increases the infiltration rate declines and normally approaches a constant value which is called the basic infiltration rate. According to Kostiakov (1932), the instantaneous infiltration rate can be written as follows:

$$i = at^b \quad 2.21$$

i = instantaneous infiltration rate (mm/h), t = elapsed time (min), a and b = soil infiltration constant. The value of c is zero when the terminal rate of water into soil is zero.

The infiltration rate is affected by many factors such as soil texture, structure, water table, hard pan beneath the soil surface, organic matter, and compaction. Withers & Vipond (1985) reported that infiltration rate may change during the irrigation season. Because the passage of water causes the movement of small particles through the soil which may block up the pores. The infiltration rate is also affected by the soil cultivation, for instance in a ridge and furrow the infiltration will be two dimensional.

Hillel (1980) reported that the reduction of matric suction gradient, formation of sealing and crust, migration of pore-blocking particles, swelling of clays, entrapment of air bubbles or bulk compression of soil air, if it is prevented from escaping and displacement of incoming water are the reasons for the reduction of infiltration rate. Kemper (1993) reported the following reasons for low infiltration: organic coating on the soil minerals which causes the soil to be hydrophobic, small pores of soil encountered by water and cause low infiltration rates and raindrops causes large pore structure to be filled with segments loosened from clods. This process is aided by low electrolyte concentration of rain water which causes swelling to develop between the particles and breaking of the bonds between the particles. Soil infiltration depends on the following factors:

2.5.1 Effect of soil water content

When the soil is dry, infiltration rate is controlled by two mechanisms, matric potential and the gravitational force. Matric potential firstly is high and operates until the soil water is on the incipient point of saturation. When the soil is completely saturated matric potential tends to zero and the gravity force causes the movement of water through the soil.

When infiltration takes place into a dry ridge and furrow the initial infiltration rate into both horizontal and vertical sides are nearly the same. Therefore,, water from a furrow firstly will infiltrate laterally almost to the same extent as vertically. However, when the soil is initially wet the suction gradients are small from start and become negligible much sooner (Figure 2.7)

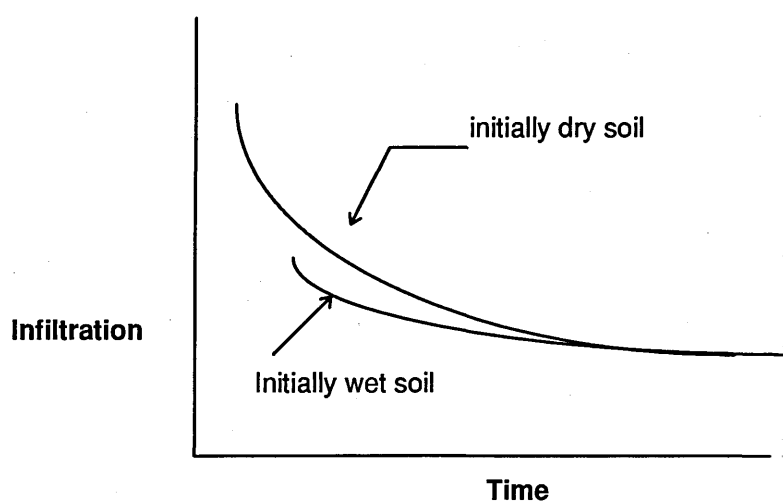


Figure 2.7 Infiltration rate as a function of time for initially dry and wet soil (source: Hillel 1980)

2.5.2 Effect of soil texture

The soil matric potential is influenced by soil texture. At the same water content, the fine textures have higher matric potential than coarse textures. This will cause initially higher infiltration capacity rates by the fine textures than that of coarse textures. However, after soil saturation the infiltration will be controlled just by gravity force and reduces to a constant value which is less for the fine textures than for the coarse textures. Macropores will be more if the soil texture is coarse or soil is quite porous due to organic matter or mulches. These pores increase the infiltration rate and specific yield. This can be found from Darcy equation. When the macropores are high the flux area that affects hydraulic conductivity will be large and infiltration will increase as follows (Hillel, 1980).

$$i = \frac{dI}{dt} = K \frac{\Delta H_p}{L_f} \quad 2.22$$

Where I = accumulated infiltration, i = instantaneous infiltration rate, L_f = the distance between two points, ΔH_p = the difference of matric potential between two points and t = the elapsed time.

According to Hillel (1980) the presence of layers which differ in texture or structure from the overlaying may retard water movement. For instance, clay layers and sand layers inside the soil profile can have similar effect, although for opposite reasons. At equal matric potential the clay layer impedes flow due to its lower saturated hydraulic conductivity, while sand layer retards the wetting front due to its lower unsaturated conductivity.

2.5.3 Effect of hydraulic conductivity

The effect of hydraulic conductivity (K) on infiltration rate (i) can be understood from the Darcy equation as mentioned in equation 2.22 (Hillel 1980). Different approaches can be used to determine the saturated hydraulic conductivity of soil. For example, falling head and constant head methods are often used in laboratory and infiltrometer, ponding time and water balance methods can be used both in laboratory and field. From them three methods will be discussed briefly here.

1 Based on falling head method the following formula can be used to calculate the saturated hydraulic conductivity of soil samples in laboratory.

$$K_{sat} = \frac{a_m \times L_c \times \ln\left(\frac{h_1}{h_2}\right)}{A_c(t_1 - t_2)} \quad 2.23$$

Where a_m = the cross section of manometer tube, A_c = the cross section of soil cylinder, L_c = the length of soil sample; h_1 and h_2 = the heads of water at times t_1 and t_2 .

2- The hydraulic conductivity can be estimated by using water balance equation for an equilibrium condition.

$$i = R + Q + \Delta\theta \quad 2.24$$

In which R = rainfall intensity, Q = runoff flow rate, $\Delta\theta$ = variation of soil water content, i = final infiltration rate ($\approx$ saturated hydraulic conductivity).

3- Based on Green and Ampt analysis, the following procedure was suggested by Young (1996) to find the hydraulic conductivity of soil at constant rainfall intensity by using time to ponding equation as

$$t_p = \frac{s_s^2}{2R(R - K)} \quad 2.25$$

Where s_s = soil sorptivity, R = rainfall intensity, K = hydraulic conductivity and t_p = time to ponding. The s_s is approximated as follows (Young, 1968 and 1991)

$$s_s = \sqrt{[2K(-h_f)(\theta_0 - \theta_i)]} \quad 2.26$$

In which h_f = the air entry value of soil water pressure and θ_0 and θ_i = the saturated and initial values of water content of soil. The s_s can be written as follows as well:

$$s_s^2 = 2 \int_{-h}^0 K(h) dh \times (\theta_0 - \theta_{i_i}) \quad 2.27$$

There is the following relationship between capillary drive (G) and hydraulic conductivity (Young 1996, personal communication). This parameter is important in the modelling of runoff which will be discussed in more detail later. The development of this parameter is discussed here.

$$G = \frac{1}{K} \int_{-h}^0 K(h) dh \times (\theta_0 - \theta_{i_i}) \quad 2.28$$

Where G = a parameter of soil called capillary drive. If equations 2.27 and 2.28 are substituted in equation 2.25 the following equation is obtained:

$$t_p = \frac{G \times K}{R \times (R - K)} \quad 2.29$$

or

$$R - K = \frac{GK}{t_p \times R} \quad 2.30$$

The equation 2.30 is applied to two different rainfall intensities at two different time of pondings as follows:

$$R_1 - K = \frac{GK}{t_{p1} \times R_1} \quad 2.31$$

$$R_2 - K = \frac{GK}{t_{p2} \times R_2} \quad 2.32$$

The difference between two last equations is as

$$R_1 - R_2 = GK \left(\frac{1}{t_{p1} \times R_1} - \frac{1}{t_{p2} \times R_2} \right) \quad 2.33$$

Thus

$$GK = \frac{(R_1 - R_2)}{\left(\frac{1}{t_{p1} R_1} - \frac{1}{t_{p2} R_2} \right)} \quad 2.34$$

And finally K will be as

$$K = \frac{GK}{t_{p2} \times R_2} - R_2 \quad 2.35$$

As illustrated by Oliveira et al (1987), it should be noticed that effective saturated hydraulic conductivity of soil progressively reduced through the season for all application rates and soil treatments. Therefore,, it should be considered in design and operating.

2.5.4 Effect of sprinkler irrigation

The mechanism of infiltration rate under sprinkler irrigation or rainfall is different from that under surface irrigation, because there is no head of water above the soil surface. The process of infiltration under rainfall or sprinkler was described by Hillel (1980). According to him, if the rainfall intensity is less than initial infiltration value but greater than the final infiltration, then at first soil will absorb water at less than its potential rate and the flow of water in the soil will happen under unsaturated hydraulic conductivity. If the rainfall or application of water continues at the same rate, the soil surface eventually becomes saturated and ponding will occur. If the rainfall intensity is always less than the saturated hydraulic conductivity the soil will continue to absorb the water as fast as it is

applied without ever reaching saturation. However, after a long time the suction gradient becomes negligible and the soil wetted profile attains a wetness for which the saturated hydraulic conductivity is equal to the rainfall rate. Therefore, the lower the application rate, the lower will be the degree of saturation of the infiltration profile.

Woolhiser et al (1990) reported that the soil infiltration process depends upon initial soil water content and the amount of rainfall the soil has already absorbed. According to them at the beginning of rainfall the infiltration is equal to the rainfall intensity and rainfall excess is equal zero. During this period the soil can absorb water at a rate greater than the rainfall rate. The maximum rate at which water can enter the soil is called the infiltration capacity (i_c). This factor can be described as a function of the initial water content of soil (θ_i) and the rainfall already absorbed into the soil (d_i) so that

$$i_c = f(d_i, \theta_i) \quad 2.36$$

Smith and Parlange (1978) used the following relationship between infiltration capacity; amount of rainfall and soil water content of soil as follows

$$i_c = \frac{K_{sat} \exp(\frac{d_i}{B})}{(\exp(\frac{d_i}{B}) - 1)} \quad 2.37$$

where i_c = the infiltration capacity of soil, K_{sat} = the saturated hydraulic conductivity of soil, d_i = the amount of rain already absorbed by soil and B = the saturated deficit of soil. Smith (1983) described two key parameters related to infiltration process. One was effective saturated hydraulic conductivity and other

was effective capillary drive. Woolhiser et al (1990) applied Smith's key parameters and the Smith and Parlange (1978) equation to simulate the infiltration rate in the KINEROS model. This will be discussed later in developing the infiltration model.

The measurement of infiltration rate is affected by the method of irrigation. Therefore,, the method used to measure soil infiltration rate under sprinkler irrigation should simulate, as far as possible the mechanism of water intake rate during irrigation. Withers & Vipond (1985) reported that the ideal method to measure infiltration rates under sprinkler irrigation rate is to spray water at various application rates. Therefore,, the methods which were described in previous section for saturated hydraulic conductivity such as time to ponding and water balance equation can be used here for this purpose.

2.5.5 Effect of crust soils

The properties of the top layer are not constant during the cropping season, and as the season proceeds it is well known that the bulk density increases and the infiltration rate reduces. In addition to this,Seals or crust is one of the main problem of soils under sprinkler irrigation systems. This can be developed under the beating action of or as a result of breaking down of soil aggregates during wetting raindrops. A surface crust can greatly impede water intake by soil, even if the crust is quite thin, e.g. not more than a few millimetres in thickness.

The mechanisms of soil crust formation have been reported by many researchers such as Evans and Buol (1968), Hillel (1980), Morgan (1986), Ben-Hur (1994) and Levy et al (1995). Two mechanisms have been reported for sealing and crust formation. The first is the physical disintegration of soil aggregates and soil

compaction due to water drops impact. The second is, the physio-chemical dispersion of aggregates and movement of clay particles into a depth of 0.1 to 0.5 mm where they block the pores between the particles. Levy et al (1995) reported that exchangeable sodium percentage (ESP) and the electrolyte concentration of soil solution is involved in the second mechanism. So the infiltration rate begins to reduce with increasing ESP and decreasing electrolyte concentration. The surface crust formation is also affected by chemical composition of irrigation water which was reported by Hillel (1980). A water with a high sodium absorption ratio (SAR), coupled with a low concentration of salts, can start dispersion and swelling the clay in surface layer of the soil. Then dispersed aggregates collapse and close the interaggregates cavities and moving clay particles also block the soil pores beneath the surface and eventually reduce the infiltration.

The kinetic energy (E_k) of rain drops striking at an exposed surface can cause soil structure to break down. This energy is a function of raindrop mass (m) and velocity (V) as follows

$$E_k = \frac{1}{2}mV^2 \quad 2.38$$

The total kinetic energy of all the drops can be calculated as (Hillel, 1980)

$$E_{kt} = \frac{1}{2}\sum m_i V_i^2 \quad 2.39$$

in which m_i and v_i = the masses and velocities of raindrops at successive size groups. The impact of raindrops on the soil surface is influenced by plant protection or mulch, surface roughness, slope, incident angle and existence of water on the soil surface.

Hoogmoed and Stroosnijder (1984) illustrated that the most important effect of surface crust is to reduce infiltration capacity and thereby increase the surface runoff. They noticed that the infiltration capacity on sandy soil in Mali ranges from 100 to 200 mm/h, but where crusting has developed it reduces to 10 mm/h. Morgan (1986) illustrated a surface crust of only 2 mm thickness may be enough to reduce infiltration and cause runoff. He also reported that on a sandy soil in Bedfordshire, England, infiltration capacity is greater than 400 mm/h and that rainfall intensities rarely exceed 40 mm/h. Thus no surface runoff would be expected. Whereas, in fact, the mean annual value of runoff is about 55 mm from a mean annual rainfall 550 mm. In Figure 2.8 infiltration rate of a crusted soil is compared with a uniform non-crusted soil and with a soil having a high permeable structure on upper layer.

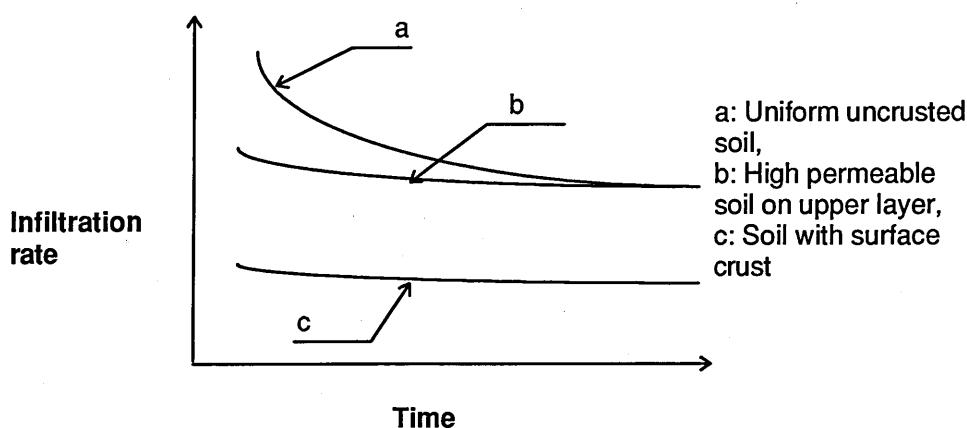


Figure 2.8 Infiltration rate as a function of time (after Hillel 1980)

Ben-Hur (1994) examined the effect of soil type on crust formation and runoff. He measured the percentage of runoff in two types of soil e.g. silt loam loess and clay loam vertisol. He found that the rate of runoff in loess (53%) was higher than in vertisol (39%). He explained the source of variation could be due to the difference in aggregate stability and / or crust formation. However, Evans and

Buol (1968) reported that the structure of soil is rarely stable. This is because the impact energy of water drops causes the surface structure to break down and a surface seal with a lower infiltration rate, greater density, higher strength, finer pores and lower conductivity than the underlying soil is formed. Hillel (1980) reported that when the soil surface is compacted, or the profile is covered by a surface crust of lower conductivity, the infiltration rate is lower than that of uncompacted, or uncrusted uniform soil. Therefore,, the surface crust acts as an hydraulic barrier or bottle neck impeding infiltration. The thicker and denser crust reduce both the initial and final infiltration rate.

2.5.6 Infiltration during recession

During rainfall, it is assumed that infiltration occurs on all the soil surface. When the rainfall ceases the infiltration continues until the complete depletion of water flow from the soil surface. Unlike the rainfall condition, the infiltration does not continue on the whole soil surface area during the recession. As a result, the infiltration during the recession is limited by the fraction of soil covered by water. The recession factor (*RECS*) was defined by Woolhiser et al (1990) as the local maximum average depth of surface water flow for which the whole area have been covered by water. When average flowing water depth (h_{av}) is reduced below this depth the covered surface area is assumed to be reduced. Therefore,, when the local average depth is half of the (*RECS*), it is assumed that the half of area is under flowing water. A very low value of recession (*RECS*) factor represents a relatively smooth area such as a recently-prepared seed bed. A very large value of *RECS* indicates a very rough or rilled surface such as one recently ploughed with a mouldboard (Woolhiser et al, 1990, Morgan et al 1992). Infiltration rate in this stage at time (t) is equal to infiltration rate at time step ($t-1$) multiplied by a fraction of area covered with water ($h_{av} / RECS$) as follows:

$$i_t = \frac{i_{t-1} \times h_{av}}{RECS} \quad 2.40$$

Where i_t = infiltration rate at time t , i_{t-1} = previous time step, h_{av} = local average flow depth and $RECS$ = local maximum average depth of flow.

2.5.7 Effect of ponding depth

Water begins to pond on the soil surface when the soil infiltration equals the water application rate. From this time the soil infiltration rate will be controlled by infiltration capacity. If the water application continues more water will pond on the soil surface. Using Green and Ampt (1911) approach and making the following assumptions:

(i) during the infiltration there is a distinct and precisely definable wetting front and a constant matric potential at this wetting front, regardless of time and position, (ii) beyond the wetting front soil is uniformly wet and hydraulic conductivity is constant. Considering these assumptions the Darcy flow equation is simplified as

$$i = \frac{dI}{dt} = K \frac{(H_o - H_f)}{L_f} = K \frac{\Delta H_p}{L_f} \quad 2.41$$

In which i = the flux into soil and through the transmission zones, I = the cumulative infiltration, k = the hydraulic conductivity of the transmission zone, H_o = the pressure head at soil surface, H_f = the pressure head at the wetting front, L_f = the distance between soil surface and wetting front and ΔH_p = the pressure head change from the soil surface to the wetting front. According to the above

mentioned formula as the depth of ponding increases the infiltration rate also increases. This means the infiltration rate under flood irrigation is more than sprinkler irrigation in which ponding depth is quite low, with the exception of rough soil or when the soil and water conservation techniques are used to prevent runoff.

2.6 Water application rate

For a designer it is important to consider the rate of water application when selecting a sprinkler, operating pressure and spacing. The rate of water application depends on the size of the nozzle, operating pressure and the spacing between the nozzles. Decreasing the nozzle pressure, increasing the nozzle size and closer spacing will increase the application rate. The application rate should preferably be less than the basic infiltration rate of the soil to avoid surface runoff and erosion (MAFF 1974, Benami and Ofen 1983). Withers and Vipond (1985) also reported that the maximum acceptable application rate is the basic infiltration rate of the soil but a lower rate is preferable on soils to reduce damage to soil structure and crop and prevent surface runoff. According to Benami and Ofen (1983), if the soil is heavy and sloping even a low application rate may be too high and can result in ponding and runoff.

Stationary sprinkler irrigation systems are normally designed so that no runoff takes place. Thus the application rate of the systems is less than the infiltration capacity of soil or the application is ended before the surface depressions are filled with sufficient water depth to cause overland flow (Larry 1988).

As indicated in Figure 2.9, initially all water that is being applied by sprinkler enters into soil, because the application rate is less than infiltration capacity (line

B). There is no possibility of runoff until line B crosses line A and the application rate exceeds the infiltration capacity. Runoff will still not happen until all the depression storage is filled with water and sufficient depth of water to cause flow is accumulated. The amount of water accumulated in depression storage and on the soil surface (before runoff starts) depends on the depth and the extent of

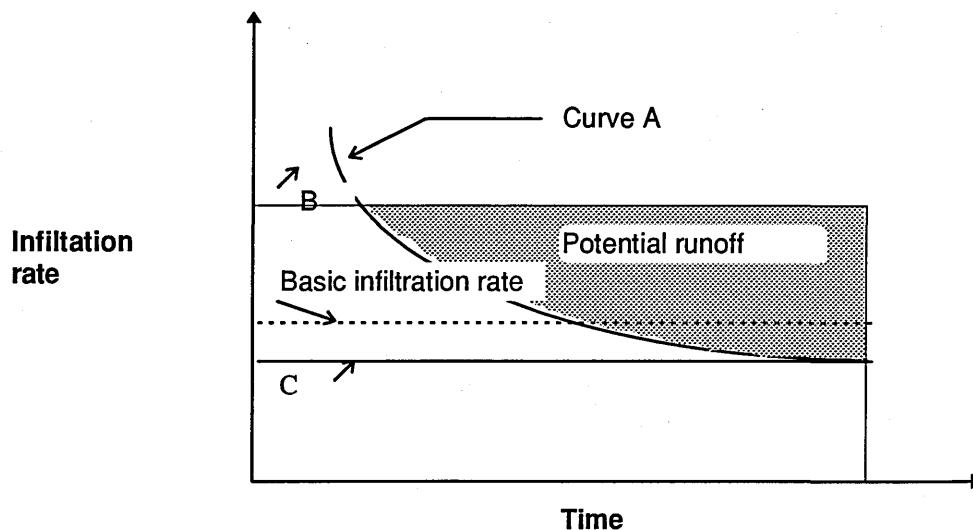


Figure 2.9 Infiltration capacity of soil and two application rates (after Larry 1988)

depressions, soil surface slope, amount of residue, vegetation and tillage operations.

Line C shows a constant application rate that never exceeds the infiltration capacity. Thus the application rate can continue indefinitely without runoff. The maximum application rate is equal to basic infiltration rate. The minimum application rate depends on the frequency of irrigation and required time to apply the required depth of irrigation water. The higher the frequency, the lower the minimum application rate tends to be. The optimum application rate is between

the maximum and minimum rate. Sprinkler spacing, operating pressure and nozzle sizes will nearly provide the optimum water application rate with the greatest uniformity. Water application rate under moving sprinkler is different from that of under stationary systems, although the application depth may be same. This is because the water application rate under the stationary sprinkler systems is constant at a point (Figure 2.9), but it changes with time for moving sprinkler systems (Figure 2.10).

Over recent years many high pressure impact moving sprinkler irrigation systems have been replaced by low pressure systems in order save energy. This is because the energy costs are directly related to operating pressure. In this case

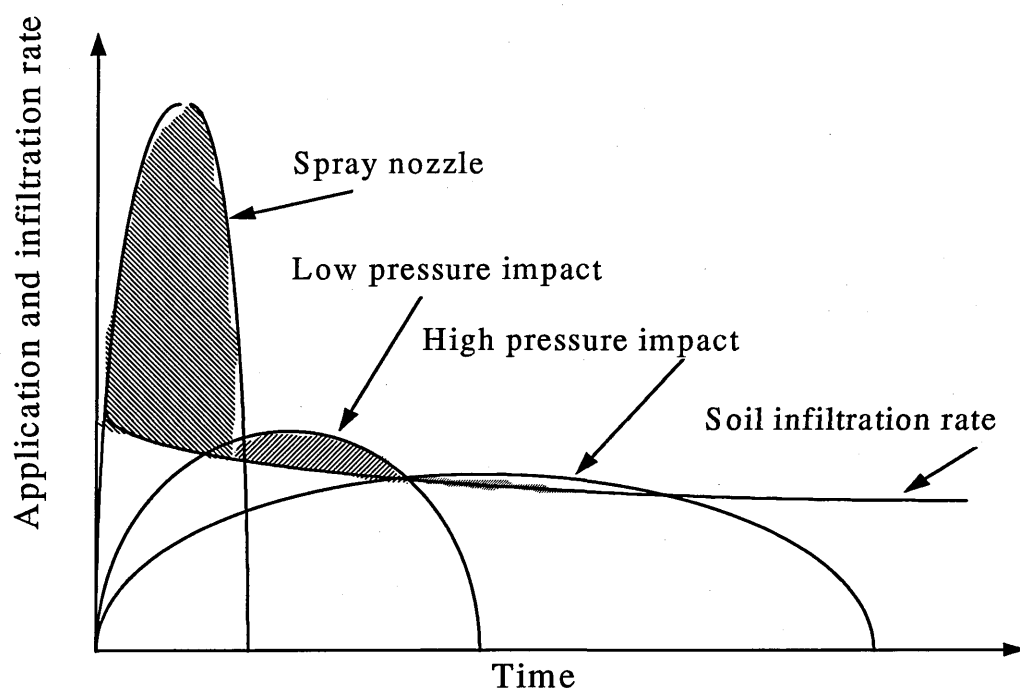


Figure 2.10 Water application rate, infiltration rate and potential runoff under high and low pressure centre pivot irrigation system (Gilley and Mielke 1980)

the maximum water application rate of low pressure, using either impact or spray nozzles is greater than that of high pressure systems (Figure 2.10). Bernuth and Gilley (1983) and Hasheminia (1994) reported that low pressure application rates may lead to one or more of following problems: (i) increased application rate and reduced application time due to reducing wetting area, (ii) increased droplet size due to increased in nozzle size or decreasing in pressure and (iii) reduced uniformity of water application rate due to reduced wetted area and (iv) high application rate associated with low pressure sprinklers causes runoff and erosion on all soils, except the more permeable ones. Most high pressure impact sprinklers apply water as a jet that wets a point on the soil surface once or twice each rotation of the sprinkler head. Low pressure impact sprinklers systems wet a smaller area than conventional high pressure sprinkler and thus have higher application rates. Low pressure fixed spray nozzles or rotary sprinklers normally apply water as a spray that covers the whole wetted area continuously or as a diffuse stream that wets a point on the soil once or twice each head rotation. Therefore,, the rate at which water is applied at a point on the soil surface during an instant time is more for low pressure sprinklers than for high pressure sprinklers. The application rates of three different applicators such as high rotary impact pressure sprinkler, low pressure rotary impact sprinkler and fixed spray nozzle are compared in Figure 2.10. The amount of applied water by each applicator is the same but application patterns are different both in time and magnitude. For the same discharge, the spray nozzle with the smallest wetted area has the highest application rate and this creates the highest potential runoff. The low pressure impact sprinkler can cause potential runoff on a soil with a low infiltration rate.

Amir and Alchanutis (1992) defined the instantaneous application rate (IAR) as the discharge per unit area per unit time at a given time. High IAR reduces application time and increase the capacity of mobile irrigation machines by

increasing the speed of movement and discharge. High IAR is one of the characteristics of moving irrigation machines such as centre-pivots. This will be further increased by the use of low pressure, which reduces the wetted area. Non uniformity of water application pattern may increase the IAR locally. If IAR exceeds the infiltration capacity this may cause runoff, increase soil erosion and reduce irrigation efficiency. The most efficient way to have high machine speed, high discharge and low pressure (while avoiding high IAR) is to control both instantaneous and cumulative water application. This can be done by controlling type and diameter of nozzle, jet impact plate, pressure head, spacing of nozzle and height of emitters.

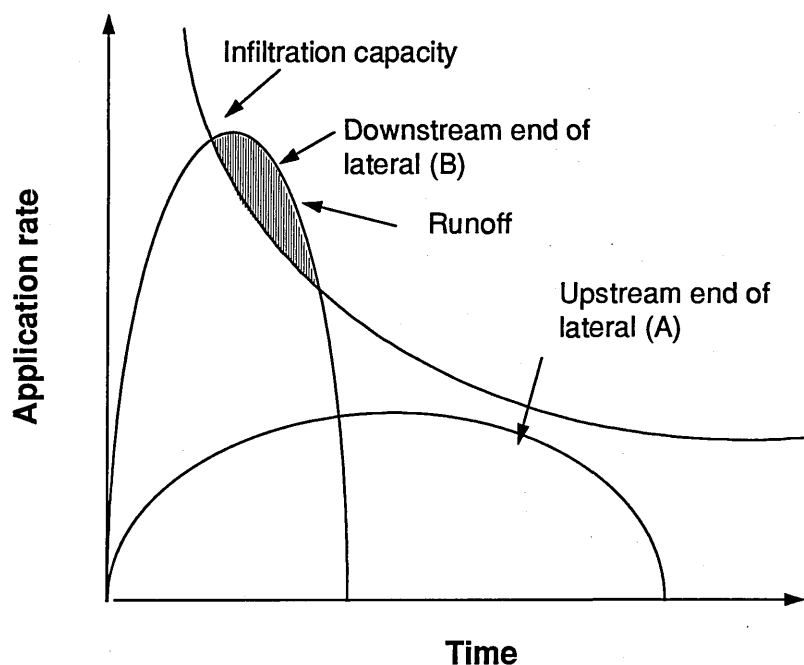


Figure 2.11 Relationship between infiltration capacity of soil and application rates beneath centre pivot laterals

Application rates under travelling rainguns or centre pivots increase to a peak and then reduce to zero as the traveller approaches and then passes over a particular point in the field. Many times, the peak application rate exceeds the infiltration capacity and causes runoff (Figure 2.11) (Larry 1988).

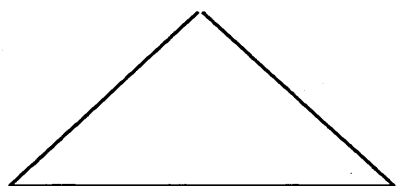
Increasing water application rate from the centre to the end tower is another characteristic of centre-pivots. This design is required to get a uniform irrigation design depth all over the field. Consequently the risk of centre pivot runoff increases from the centre to the end tower. If the application depth or the time of revolution increases, the potential runoff will increase and occur closer to the pivot centre (Larry 1988 and Ben-Hur 1994).

Figure 2.11 indicates the variation of application rate with time for a centre-pivot at two different speeds. One is for the end of tower in which the speed is high and peak application rate exceeds the infiltration capacity (B) and the other is close to the pivot in which the speed is low and the peak application rate is less than basic infiltration rate but for a longer period (A). The depth of applied water, i.e. the area under the curves, is the same.

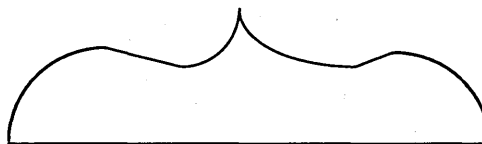
2.6.1 Water distribution pattern

It is difficult to design a sprinkler irrigation system to produce a uniform water distribution pattern over the whole wetted area. This is because the application rate is normally heaviest close to sprinkler and reduces toward the edge. The application pattern is shaped like a triangle, doughnut or trapezoid, depending on operating pressure (Figure 2.12) (MAFF 1974; Benami and Ofen 1983). The triangle arrangement gives the greatest uniformity for sprinkler spacing followed by square arrangement and lastly by conventional rectangular layout. According to Zimmerman (1966), uniform water distribution patterns can only be obtained

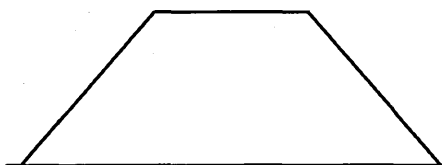
from a sprinkler operating at its optimum pressure. With regard to the kind of discharge profile (triangle, trapezoid, rectangular and parabola), he found maximum uniformity for the different percentage of overlapping (spacing along main axis as a percentage of wetted diameter). For example, the triangular profile yielded the maximum value of uniformity coefficient (C.U.) in the range of spacing 50 to 59 %. He reported that C.U. decreased as the overlap percentage increased. Willardson et al (1987) found that when sprinkler spacing is half of the wetted radius the uniformity increases, the closer the sprinkler the higher the water application rate. It should be noted here the distribution of water applied at the soil surface is not necessarily the same as in the soil, due to redistribution within the soil.



a- Triangle (correct shape)



b- Doughnut (low pressure)



c- Trapezoid (high pressure)

Figure 2.12 The effect of operating pressure on water application pattern by sprinkler

2.6.2 Wind effect

Wind can easily blow spray from sprinklers and distort the distribution pattern and upset the irrigation uniformity. To reduce the effect of wind, the sprinkler can be brought close together. The higher the wind speeds are, the closer the required spacing of sprinklers must be. Although 5 m/s is only thought of as a gentle breeze, it will seriously distort the operation of a sprinkler system. In this condition sprinklers should be very close together to get a good uniformity. The designers prefer to place the lateral at right angles to the dominated wind direction and reduce the sprinkler spacing along the lateral. This is not always practical for centre pivot systems. Therefore, the water application pattern of centre pivot is more distorted than conventional sprinkler systems. Wind has more effect on wider spacing, larger sprinklers and twin nozzle sprinklers (MAFF 1974).

Wind speeds above 13 kilometre per hour have a serious influence on water distribution. To reduce the effect of wind, it is not always practical to reduce the lateral and sprinkler spaces, because it leads to a higher application rate if the sprinkler size is not changed. The performance of twin nozzle sprinklers can be improved in windy conditions by plugging the inner nozzle and using the range nozzle only. Decreasing the height of the riser can also improve performance in wind.

As illustrated by Benami and Ofen (1983), in the absence of wind, the wetted area of a single sprinkler is circle. In windy condition the circle is shifted relative to the sprinkler in the direction of the dominant wind (Figure 2.13). The size of wetted area and the distribution of water over it depends on the pressure, type, trajectory angle and diameter of a sprinkler nozzle, driving mechanism and speed of rotation, height of riser and wind condition. Musharie (1993) reported that the

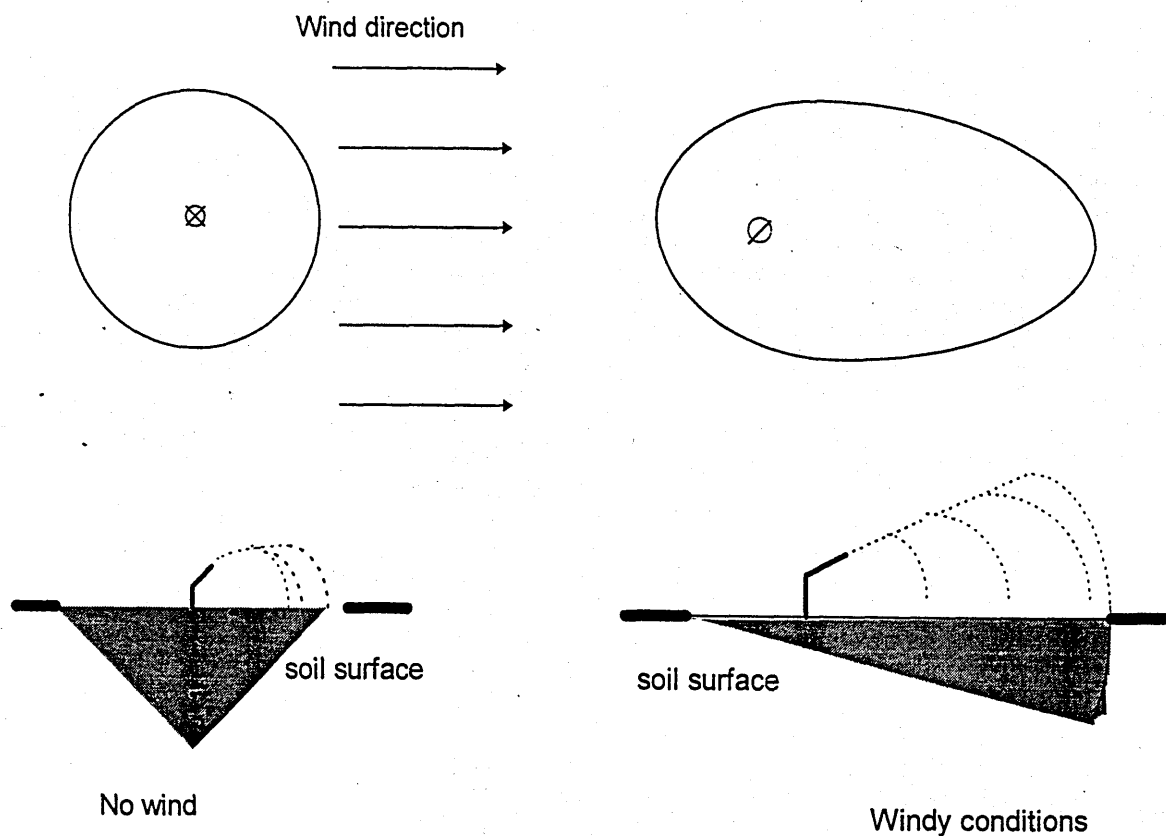


Figure 2.13 The effect of wind on sprinkler performance

trajectory angle had a little effect on water distribution at zero wind speed condition. However, as the wind speed increased the distribution was influenced significantly.

Shul Dylia (1976), Musharie (1993), Richards and Weatherhead (1993) have shown that wind shortens the pattern upwind, narrows it at right to wind and extends the application pattern downwind. As wind increases the wetted width and wetted distance upwind decrease and wetted distance to downwind increases. Application rate also increases to downwind and each side of sprinkler perpendicular to wind direction. At high wind speeds localised application rates

may be ten times the average of the pattern. However, the proportion of downwind increasing is less than the upwind decreasing. Therefore,, the wetted area decreases as the wind velocity increases.

According to Fukui et al (1980) wind direction has a small effect on uniformity coefficient (C.U.). They also confirmed that wind drift of sprinkler spray on C.U. can be neglected for wind velocity less than 1 m/s. They also found that when the velocity of wind increases there is a little increase in wetted diameter downwind and wetted area increases as the wind direction with respect to sprinkler changes. They found that the maximum C.U. for triangular profiles occurs at low sprinkler spacing and trapezoidal profiles at long spacing. Overall, wind drift is important factor which should be considered in designing and operating.

2.6.3 Pressure effect

Nozzle pressure is an important factor in sprinkler irrigation design and operation. It affects the water application pattern, trajectory angles and uniformity. Sprinkler nozzles were classified into three categories based on, low, medium and high pressure by Withers and Vipond (1985) (Table 2.1). Medium pressure sprinklers which operate at correct pressure and appropriate spacing give good uniform coefficient are now widely used. However, the high and the low pressure effects have been studied by several investigators. In this direction two extreme pressures have been acknowledged by MAFF (1974); Withers and Vipond (1985). The first one is when the pressure is high, the jet of water breaks up into very small particles and misty. From them part will be carried away by the slightest breeze, part will be evaporated before reaching the soil surface and the rest will fall close to the sprinkler head leaving most of field dry. The second extreme is when the pressure

Table 2.1 Sprinkler classification for different pressure (source Withers and Vipond 1985)

Type	pressure (bar)	Diameter (m)	Discharge (m ³ /hr)	Application rate (mm/hr)
Low	0.7-2	9-25	0.15-1.5	2.5-25
Medium	2-4.7	20-45	0.55-5.5	3.3-45
High	4.7-9.3	35-120	4-11	7.5-48
Raingun	1.3-4.7	20-60	10-40	5-18

is low, the water jet is not broken up thoroughly, and as a result, the wetted area is reduced. Large water drops fall on the ground with force which can cause crusts to form and seal the soil surface against penetration. The crusting is especially harmful during germination.

Although a high pressure raingun or giant sprinkler covers a large area, the cost is relatively low and it is simple to operate. However, there are some limitations for its use. The application rate is high and drop sizes tend to be large. To use such equipment, infiltration rate must be high and soil structure and crops must be stable and non-sensitive to resist the impact of drops. The medium pressure sprinklers have the advantage of low energy requirement and the disadvantage of more equipment being required.

2.6.4 Uniformity

The uniformity of applied water can be assessed in different ways. The most widely known approach was suggested by Christiansen as follows:

$$C.U. = 100 \times \left(1 - \frac{\sum |x_i - \bar{x}|}{N \bar{x}} \right) \quad 2.42$$

Where $C.U.$ = uniformity coefficient, X_i = observed depth of water, $\bar{X}$ = the averaged applied depth of water in catch cans and N = the number of catch cans.

Wilcox and Swailes (1947) gave the following relationship which is based on standard deviation (s)

$$C.U. = 100 \times \left(1 - \frac{s}{\bar{x}}\right) \quad 2.43$$

Where $\bar{x}$ is the average of observed values, $s / \bar{x}$ = the coefficient of variation. Among these three methods, Christiansen method is selected for this study. Because it is now standard method in the new irrigation equipment standard (ISO/7749-2 1995).

Benami and Hore (1964) proposed different approaches .One of them is as follows:

$$C.U. = 166 \frac{N_a}{N_b} \left[\frac{2T_b + D_b M_b}{2T_a + D_a M_a} \right] \quad 2.44$$

Where

M_b = the mean value of the group of measurement below total mean value

M_a = the mean value of the group of measurement above total mean value

N_b = the number of measurements below total mean value

N_a = the number of measurements above total mean value

T_b = the sum of the measurement below M_b

T_a = the sum of the measurement above M_a

D_b = difference between the number of measurement below and above M_b

D_a = difference between the number of measurement below and above M_a

Benami and Ofen (1983) noticed that to achieve an acceptable distribution uniformity there should be a sufficient overlap of wetted area of adjacent sprinklers. The degree of overlap depends on the kind of nozzles and pressure, and wind condition. Less overlap is considered for distribution patterns which are more or less trapezoid shape than for triangular shape. Thus the sprinkler can be spaced further apart. For sprinklers, having trapezoid distribution the corresponding spacings are 70 to 75% of wetted diameter for high wind speed. If the sprinklers are spaced too far apart, a lower uniformity coefficient and reduced crop yield will result. When the wind is light the distance between sprinklers is expected to be 60 to 65 % of wetted diameter and on lateral 40% which could produce an acceptable triangular distribution pattern. To get a good uniformity, watering at early morning or late afternoon is most suitable one, due to light wind condition. A value of uniformity coefficient of 100 % means the irrigation is completely uniform, this is not obtainable in practice, but 95 % have been obtained. In general, a uniformity coefficient more than 75 % is a reasonable value (Morgan 1995, personal communication). If the design area has ample rainfall during the irrigation season lower value can be acceptable. To get a uniform water distribution, a number of sprinklers are operated close together, so that the distribution pattern overlaps, nearly 65% of wetted diameter. To see how uniform is the water application rate for stationary sprinkler systems in the field or laboratory, a square grid of catch-cans can be used. The system is operated for a short time and then the depth of collected water is measured in each of the cans for uniformity determination. Uniformity of water distribution for a mobile system can be tested by setting a line of cans across the traveller path of the machine. The factors such as wind and operating pressure can seriously affect uniformity of water distribution.

2.6.5 Drop sizes

Water drops affect the flow regime, application rate and soil surface and their sizes depend upon nozzle size and pressure. At a given pressure, drop sizes increase as the pressure head drops. The larger drops fall far from the sprinkler and close to boundary of wetted area and small drops fall close to sprinkler. Kay (1983) and Withers and Vipond (1985) reported that a nozzle normally produces a wide range of drop sizes from 0.5 to 4 mm in diameter. Drops larger than this tend to break up into smaller size. Large drops may damage delicate crops, breaking down the soil structure and cause soil capping and reduce infiltration rate. Withers and Vipond (1985) acknowledged that the range of drop size can be controlled by the size of nozzle and its operating pressure. At lower pressure drops tend to be larger. At higher pressure they are much smaller and misty may occur. Medium and low pressure sprinklers produce drop size within the range of 1 to 4 mm. The drop sizes from raingun which are above 4 mm widely disperse.

Woolhiser et al (1990) reported that raindrops influence overland flow (i.e. runoff). The impact of drops on the water film on the soil surface generate local area of turbulent flow and have the same effect or are similar to the water viscosity. For a laminar flow over a hydraulically smooth surface the friction factor (f_d) for Darcy-Weisbach equation will be

$$f_d = \frac{24}{R_n} \quad 2.45$$

The raindrop impact change the above equation as follows:

$$f_d = \frac{k}{R_n} \quad k > 24 \quad 2.46$$

$$k = k_0 + f(r)$$

2.47

In which k_0 = the appropriate value for a given surface geometry without raindrop impact and $f(r)$ = function of rainfall. The impact of raindrops is important for a smooth surface such as laboratory catchment. They are not significant for hydraulically rough surface which usually found in field.

2.7 Soil and water conservation techniques

Potential runoff can be reduced or controlled by adjusting system pressure and application rate, increasing moving sprinkler speed, or using different soil and water conservation techniques. In order to conserve soil and water and prevent runoff one or a combination of any following procedures can be followed:

2.7.1 Land slope reduction

Land slope reduction affects runoff and erosion in two ways: (i) reduces runoff velocity and erosion and (ii) affects water application depth and distribution uniformity. In agricultural areas runoff and erosion can be controlled by land slope reduction. When the slope is reduced the velocity of runoff and erosion will also reduce.

To break the land slope means to level the land and to give a reasonable slope to soil surface. Levelling is not always possible or beneficial, especially when the catchment is large. For this reason terrace levelling is suggested as a levelling technique on vast steep slope areas.

The position of sprinkler risers on steep sloping land is also important. Soares et al (1991) reported that the distribution uniformity increases for increasing nozzle angles and as the riser angle is changed from vertical angle position to normal position to the soil surface. Therefore,, sprinkler risers should be kept nearly perpendicular to the land surface under all surface condition to maximise water application uniformity and minimise runoff and risk of soil erosion. Risk of erosion on steep slopes is greatest for vertical risers.

According to Soares et al (1991), the maximum depth of water applied up slope from a single sprinkler is increased as the ground slope increases. Because the wetted distance up slope decreases as the ground slope increases. This causes higher intensity and higher depth of water applied per unit area, since the volume of water applied by sprinkler remains constant. Overall, the land slope and sprinkler risers position can be controlled to conserve soil and water on the steep slopes.

2.7.2 Mulching

Mulching is another technique which is used to conserve soil and water. Many different material can be used, depending on the situation and availability of material. Sand or gravel mulches on the surface of the fine texture can protect soil from beating and sealing action of rain drops and maintain high infiltration rates and reduce evaporation. Organic mulches and biofactors create macropores which increase infiltration and reduce runoff.

As reported by Gilley and Kottwitz (1994) runoff from Low-Energy Precision Application (LEPA) systems can be reduced by providing sufficient surface storage such as depression storage, micro-basin and crop residue. Surface

storage volume provided by micro-basins is much greater than those provided by depression storage or crop residue. They suggested that although the amount of water stored by individual ponds may be very small, the accumulated volume created by a large number of small ponds can be considerable. They developed a series of equations as follows to estimate the maximum surface storage (y) provided by crop residue as a function of residue cover (c), average slope (S) and diameter of crop residue (d_c). Two cases were considered for deriving these equations.

Case 1: This is when the average slope (S) is larger than or equal residue cover (c):

$$y = c \times d_c \left(\frac{1}{2S} - \frac{\pi}{8} \right) \quad S \geq c \quad 2.48$$

Case 2: This is when the average slope (S) is smaller than the coefficient of crop residue cover (c):

$$y = d_c \left(1 - \frac{S}{2c} - \frac{\pi c}{8} \right) \quad S < c \quad 2.49$$

where y is maximum surface storage depth and d_c = diameter of crop residue. These three independent factors (i.e. S , d_c and c) can be estimated under the field conditions. These equations were derived assuming that residue elements were oriented end to end, perpendicular to flow direction and at uniform intervals.

Gilley and Kottwitz (1994) found that the greatest increase in surface storage occurs for small amounts of residue cover. For a very large amount of residue, the effective storage capacity is occupied by crop elements. Thus on a very flat surfaces, the effect of increased surface cover is to reduce effective cross-sectional area. On steep slopes, surface storage depths are consistently

increased with greater residue cover, and provide greater effective cross-sectional storage area. Under field condition the size of residue is widely variable. Therefore,, an average value of residue material can be used. The next point is that residue elements are often oriented randomly, thus surface volume can be expected to be reduced significantly. Under the field conditions, lateral movement of water around residue will reduce effective storage. Oliveira (1987) stated that mulch thickness is important and a combination of pitting and mulching have more effect on reducing runoff and increasing hydraulic conductivity.

Ben-Hur (1994) found that the percentage of runoff from unmulched soil was higher than in the mulched soil. This greater percentage was caused basically due to seal formation on the soil surface. In fact, the impact of energy of the water drops caused the soil surface structure to break down and form the seal with the result of reduction in infiltration rate. Losirikul et al (1989, 1991) reported that furrow mulching was effective in reducing soil erosion. Measuring the soil erosion and particles resulted that small particle content such as silt and clay and soil loss were highest in 0% mulch, followed by 40, 60 and lowest in 80 percent mulch rate. They also reported the smaller particle sizes were more erosive at most slope length.

Ben-Hur (1994) and Ben-Hur et al (1995) measured the surface runoff under a moving sprinkler irrigation system to find the effect of canopy on runoff for four types of crop; cotton, potato, corn and peanut. Runoff was only 10% at the first irrigation and then increased in subsequent irrigation to an average value of 37.5%. This is indicated that the effect of crop canopy on runoff is limited. This is because early in the irrigation season, when the canopy is small and a large part of soil is exposed to drop impact, a seal is formed and runoff increased. Later in the season when the canopy is large, drying time of five days or less between

successive irrigation is not adequate to break down the crust. Consequently, runoff remains high, even after a full canopy growth. They also reported that the runoff percentage from potato was higher than the three other crops due to the difference between the seed beds of these crops. Cotton, corn and peanut were planted in beds while potato was planted in ridges with a slope of 20%. Overall a crop canopy protect a soil surface from the impact of water drops but does not reduce runoff significantly.

2.7.3 Surface storage

It is possible to reduce surface runoff by making surface storage such as pitting and micro-basins also called furrow diking or small check dams. These simple structures store the rainfall on the soil surface for a longer time and allow it to infiltrate into the root zone and further to penetrate below the root zone in soil.

Hashemina (1994) and Harold et al (1996) reported the opinions of researchers about furrow diking. According to these reports, by 1950, furrow diking was abandoned due to the slow operating speed of diking tools, little benefit in yield, weed control and difficulty with seed bed preparation and cultivation tillage. However, this method was renewed in the U.S. in the 1970s with the improvement of furrow diking equipment and further research on the substantial reduction of runoff and erosion and the consistent increase in yield.

Chain diking is a new method of forming basins in flat-tilled land. This was developed by Texas Agricultural Experiments Station to impound and conserve precipitation water. Harold and Lewis (1996) reported that chain diking reduced runoff an average of 40% compared with nondiking over three years research. The runoff was reduced most by diking when the annual rainfall was the least.

Reservoir tillage is a recently developed method which is created by a subsoiler or ripper at the depth of about 300 and spaced 700 millimetres apart, thus increasing the soil infiltration rates and additional surface storage capacity. Hasheminia (1994) carried out a series of experiments on impact of reservoir tillage on eliminating or reducing runoff over three years. He concluded that in most cases runoff was eliminated or reduced to less than 4% with reservoir tillage, compared to conventional tillage 14%. Where the runoff was not eliminated, it was due to overtopping and washout of reservoirs, especially on the steepest slopes. As a result the water use efficiency under low pressure centre-pivot irrigation was improved significantly. According to him the soil water in the conventional plots was highest in the lowest quarter of plots due to runoff movement. Reservoir tillage was found to be effective in minimising the variation of soil water levels between high elevation points where runoff occurs and low levels where it does not.

Losirikul et al (1989) also reported the effectiveness of simple interception ditches in controlling surface runoff and erosion from sloping farmland. Interception ditches, as expressed by Holy (1980), are designed to divert runoff and enhance infiltration into soil, for areas with slopes of up to 29% and are extremely susceptible to erosion. They concluded that soil losses decreased with an increase in the number of interception ditches. Nakano et al (1986) and Losirikul et al (1989, 1991) reported that the soil losses increased as the ridge lengths increased. Furthermore, they found that the large particles become easier to carry away by the runoff water with increasing the length of ridge slope. Therefore,, a ridge length should be short, if it is constructed in up and down direction to reduce the erosion. The more the slope length is shortened by ditches, the less soil loss occurs. A ditch with a space of 10m or less was proven to be effective as a factor in controlling soil loss. They recommended this space for agricultural areas which where susceptible to erosion.

2.7.4 Use of polymers

It has been recognised for several years that polymers could modify the physical soil structure. But it was not recommended to use them in agricultural area due to their cost and difficulty of application in the field. Polymers affect soil stabilisation in two ways:

- (i) polymer molecule acts as a bridge between two soil particles in an aggregate by bonding with them,
- (ii) polymer molecules are absorbed by clay surface cause a physio-chemical change on clay surface, thus reducing repulsive force among clay particles. Ben-Hur (1994) carried out a series of experiments by applying two types of polymers, e.g. polyacrylamid (PAM, 20 kg/ha) and polysaccharide (PS, 40 kg/ha). Both polymers were applied on two types of soil surface, say vertisol and loess soil. He reported that the runoff was significantly lower in the PAM and PS treatments than in the control for both soils. However, he found that application of PAM is a problem due to low solubility and high viscosity of PAM. Therefore, , the application of PS in the field is more convenient than PAM application.

Levy et al (1995) performed a series of experiments on polymers effects on runoff and soil erosion from sodic soil. They found that PAM was efficient in controlling runoff at low exchangeable sodium percentage (ESP) levels and inefficient at high ESP levels. At medium ESP level, PAM effectiveness in runoff control was changeable with water quality and polymer concentration. Research on using polymers for soil and water conservation purposes still is going on to find the best practical and economical materials and application methods.

2.8 Runoff and soil water distribution

Nonuniformity distribution of soil water content along a slope is a side effect of surface runoff and erosion. This phenomenon is undesirable in evaluation of efficiency and uniformity of crop production. Because this will lead to a low crop yield at the top of the slope and high crop yield at the base of the slope where runoff is directed. Ben-Hur et al (1994) examined the effect of surface runoff on uniformity of water distribution and peanut yield. They used two treatments: microbasin treatment and control surface treatment. In the first treatment, microbasins were constructed 1 m apart along the furrows. These basins trapped potential runoff water during irrigation and allowed it to penetrate the soil. In the second treatment runoff was allowed to run down the slope freely. Consequently the peanut pod yield in the microbasin was high, nearly 7170 kg/ha and approximately constant along the slope. The pod yield in the control treatment was 5420 kg/ha at uphill site, increasing to 6730 kg/ha at downhill site. Similar results were found for peanut canopy yield. They concluded that the reason for increasing the yield along the control slope was due to runoff down the slope, increasing the opportunity time for infiltration in the downslope direction. Conversely the microbasin trapped the runoff and allowed water to penetrate the soil and no significant difference was observed between upslope and downslope.

Jiusheng and Kawano (1996) found that mainly initial soil water content of soil and its uniformity, not water application uniformity, are dominant factors affecting the uniformity of water content within the root zone. Therefore, the criteria of water application uniformity, for example, more than 75%, may not be the most economical one, if the main purpose of system design is to produce a uniform soil water distribution.

2.9 Conclusions

In recent years much attention has been given to more water use efficiency as a mean for saving water. According to the literature most researchers agree that water saving can be made by reducing surface runoff under sprinkler irrigation systems. The high rate of water application and low infiltration rate increase the potential of runoff of applied water. Water surface runoff may cause erosion, nonuniformity in soil water content, depletion of fertilisers and pesticides and finally reduce crop production and increase environmental pollution. Therefore,, there is a need to examine the relationship between water application rate, soil cultivation practices and sprinkler irrigation systems (stationary and moving systems). A mathematical model for stationary and moving systems to predict runoff under different application and infiltration rate could be a useful base for sprinkler system design and management.

2.10 A review of modeling approaches to runoff prediction

There are many rainfall runoff models available to predict surface runoff under different rainfall intensities in large watershed areas. However, the accuracy of these models is quite different for specific hydrological conditions and many, if not most, have not been examined to adequately fit small catchments such as those irrigated by sprinkler irrigation methods. Adapting existing hydrological models to sprinkler irrigation, rather than starting to write a new model, can be considered.

There are a number of predictive models in hydrology such as stochastic models that analyse the statistical properties of a set of data to predict the probability of occurrence of an event in the future. Parametric or black- box models are another approach which tries to find a mathematical expression between different input

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There are a number of predictive models in hydrology such as stochastic models that analyse the statistical properties of a set of data to predict the probability of occurrence of an event in the future. Parametric or black- box models are another approach which tries to find a mathematical expression between different input

and output parameters. There are also deterministic models based on physical laws to calculate a quantity from inputs by determining the effect of all properties causing that event such as runoff from drainage basin properties (Weyman 1975).

A deterministic model for the surface runoff and subsurface flow creates a number of practical difficulties. Firstly the relationship between static variables such as surface roughness, flow depth and hydraulic potential in the flow equation are difficult to define. Secondly dynamic variables such as infiltration rate and soil water content are highly changeable over a short distance that direct field measurement can not give useful data for the flow equation (Weyman 1975). In spite of these shortcomings many researchers have recommended the deterministic model as the most appropriate one.

A deterministic watershed model usually consists of the following elements: Input parameters that represent the relevant physical characteristics of catchment, input parameters related to precipitation and meteorological data, the calculation of surface and subsurface flow, the calculation of surface and subsurface storage, the calculation of water losses and finally watershed outflow and other outputs. This type of model comprises a series of sub-models each representing the particular hydrological process such as interception, infiltration and overland flow, etc. The type and the details of sub-models depend on purpose, overall use of model and cost of operating. So if the model is intended for purposes beyond the runoff prediction, the structure and the detail can be adjusted to suit the application (Hann et al 1982).

There are also so many soil erosion models which are used to predict runoff and erosion. These models cannot be separated from the procedure used to model the runoff generation. This is because soil erosion by water is closely related to

rainfall and runoff. Among the models, the simplest and more common method of watershed modelling assumes overland flow to be a linear system, with rainfall excess as an input and the watershed hydrograph as the system output. In fact, the response of a watershed is not linear, and basin hydraulics can be described more accurately by using the continuity and energy equation from the fluid dynamic laws (Smith and Woolhiser 1971).

Therefore, the watershed models can be an event or continuous model. A model is an event, if a single runoff event occurs over a short period ranging from say one hour to several days. The initial conditions for each event should be determined or assumed as input data. The accuracy of outputs depend on the reliability of input data. A model is a continuous model that operates over an extended period of time determining flow rates and conditions during both runoff and no runoff periods. Most continuous models consist of three runoff components, direct surface, shallow subsurface and ground water flow, while an event model may not have one or both subsurface component and evapotranspiration as well (Hann et al 1982).

Watershed models are sometimes divided into single event lumped and distributed models.

Nowadays the majority of watershed models are lumped models such as Universal Soil Loss Equation (USLE), Revised Universal Soil Loss Equation (RUSLE). This means the mean values of land use, land slope, slope length and soil characteristics, etc. are used in these models and thus total outputs of runoff or erosion will be a function of average rainfall, topography and management condition. These factors are represented by single values of parameters. Many factors affecting runoff and erosion such as slope, land use and soil properties have spatial variability and cannot be described by a single average value. Lump models, which describe an area as a single uniform unit are not suitable. In a

distributed model the area is divided into sub-units which are arranged in a sequence to form a cascade. Each unit has its spatial variation of watershed and rainfall characteristics.

Abo-Ghobar (1988) developed a numerical mathematical lumped model based on the kinematic wave theory to predict surface runoff and hence the infiltration rate from a small catchment under different application rate and cultivation practices. This model called Surface Runoff (SROFF) model was further developed to include the intercepted water by the crop canopy. Both the runoff and interception components model were validated by laboratory experiments. There was a good agreement between the results from models and laboratory experiments. Finally he suggested that it is also possible to combine both models, runoff and interception, to provide a more complete picture. However, this model is not a strong comprehensive model. This is because the runoff predicted by this model is much greater than the measured and potential runoff. This may be due to exclusion of depression storage in the model (Abo-Ghobar 1988). Secondly the side slope of ridge and furrow are only taken into account and the bed slope is ignored. Thirdly the spatial and temporal variability of input parameters are not considered in the model and Therefore,, the model works like a lump model. Overall, as reported by Abo-Ghobar (1988) this model cannot simulate the observed data in the field adequately.

A higher level and complexity models are represented by American scientists such as Areal Non-Point Source Pollution Systems, ANSWERS, (Beasley et al, 1980); Chemical Runoff and Erosion from Agricultural Management Systems, CREAMS (Foster et al 1981); the Hirsch and Barfield's (1988) model which is complex, needs intensive data and its reliance bases on modified USLE parameters and equations; WEPP (Nearing et al 1989) model which treats the local variations but time variations within a storm are neglected. However, both

time and local variation in the input parameters of catchment or precipitation are important and cannot be neglected and they should be considered in model.

With regard to the above explanation, a distribution surface runoff model in which the spatial variation of watershed and rainfall characteristics are involved could be more desirable. KINEROS, a Kinematic Runoff and Erosion Model (Woolhiser et al 1990) and EUROSEM, European Soil Erosion Model (Morgan et al 1992) are adapted as distributed models. In spite of their complexity, input data requirement and operating costs (computers), these models are more acceptable for sprinkler irrigation design and management. This is because the European Soil Erosion Model (EUROSEM) is a comprehensive model which can simulate all the variations in soil and water characteristics which normally exist in the field. On the other hand, it was developed by a joint effort of European scientists (Morgan et al 1993) which could be more reliable. This model is linked to the KINEROS model which is also a distributed single event model and was developed to predict surface runoff as rainfall excess and routing runoff and sediment over land (Morgan et al 1992).

The KINEROS model was already validated against observed runoff data (Woolhiser et al 1990). Therefore, this model which can predict runoff from moving storms, may also predict runoff from a moving sprinkler. To use this model to simulate runoff from sprinkler irrigation, an agricultural watershed can be divided into sub-units and arranged as a cascade, whilst each unit can have its own characteristics and specific start time to apply water.

The KINEROS is a comprehensive model when it is coupled with EUROSEM. This is because depression storage factor is not included in KINEROS and most other hydrological models. However, it is included in the EUROSEM model (Morgan et al 1992) and this can be used to assess the soil and water

conservation techniques in an agricultural area. In addition EUROSEM simulates the interaction between rill and interrill erosion where water and sediments are transported from interrill area to rill. Therefore, this model may be used to predict runoff from a cultivated field e.g. a ridge and furrow cultivation, if the slopes and bed are considered interrill and rill respectively.

Furthermore the EUROSEM model simulates the vegetation cover by using a physically based approach. Vegetation is described by height, leaf shape basal area and percentage of cover. A more detail of runoff modeling is discussed in chapter 3.

2.10.1 Conclusions

Although the Abo-Ghobar (1988 and 1990) model can predict surface runoff on a micro-catchment, it cannot simulate observed data in field adequately. On the other hand this model is a lumped model and cannot predict runoff from a cascade and moving sprinkler even on a micro-catchment. Therefore, this is not a comprehensive model and is rejected as a precise tool for the prediction of surface runoff for sprinkler irrigation system design and management purposes.

Among the existing models the KINEROS and the EUROSEM models are selected to simulate runoff from a stationary and moving sprinkler in this study. Based on the objectives any of these two models will be tested. For example, if the effect of conservation techniques; effect of crop cover; interrill , rill erosion and runoff are objectives, the EUROSEM model is preferable, otherwise the KINEROS model will be used. Presumably the first attempt is to develop a model to simulate runoff from sprinkler irrigation systems. This will be done in the next chapter. Then the results from this model and that of two selected former models

briefly will be compared with observed runoff data collected in the laboratory and in the field. Then the final decision about model selection will be taken for the runoff simulation for both stationary and moving sprinkler irrigation conditions.

CHAPTER 3

MODEL DEVELOPMENT

3. Model Development

3.1 Introduction

The purpose of this chapter is to develop a kinematic wave model so that it can simulate surface runoff from an agricultural micro-catchment under sprinkler irrigation conditions.

Although an attempt was first made to develop a new model based on the basic principles of kinematic wave theory, the review in chapter 2 (section 2.10) indicated that an existing model, KINEROS modified to EUROSEM, could be suitable for adaptation to micro-catchments such as those occurring from different cultivation practices and be applicable to both stationary and moving sprinkler systems. Both approaches are developed in this chapter, namely the new model working from basic principles named OLF, and the modification to the KINEROS / EUROSEM model. A comparison of the output for the two approaches is made in order to decide on the most appropriate way for future modeling.

OLF model

In this section a mathematical process based on kinematic wave theory is discussed in order to develop a model to predict runoff. This model is applied to both simple plane and ridge and furrow cultivation for stationary and moving sprinklers. This model was named Overland Flow model and for easy expression it will be called OLF model.

3.2 Background to kinematic wave theory

The kinematic wave theory was first put forward by Lighthill and Witham (1955) for dealing with floods in rivers. The term “ kinematic “ was used to describe the properties of waves given by the continuity and stage discharge

relationships such as Chezy, Manning or Darcy-Weisbach formulae. Wooding (1965) applied the kinematic wave theory to overland flow from a V-shaped watershed consisting of two rectangular planes and a straight channel.

According to Henderson (1966) the runoff problem had been traditionally regarded as part of hydrology rather than hydraulics. However, a notable exception to this approach has been the development of a Japanese school of hydraulic engineers who attacked the runoff problem using the kinematic wave theory. Since then kinematic wave models have been considered as the ideal models for the prediction of overland flow and erosion by other researchers such as Takasao and Takara (1988), Abo-Ghobar (1988), Woolhiser et al (1990) and Morgan et al (1992).

3.3 Model development for a simple plane surface

The kinematic equations are based on continuity and momentum. According to Woolhiser et al (1990) these equations do not accommodate backwater and waves have little effect on them. In the kinematic equations the dependent variables are velocity (V) and depth (h) and independent variables are distance (x) and time (t) (Kibler & Woolhiser, 1970). Overland flow on a plane and channel is classified as a spatially varied unsteady flow. The basic equations of kinematic models are derived from the principles of conservation of mass and momentum. The schematic of overland flow on a simple plane is shown in (Figure 3.1). This simple overland flow case-approach was adapted by a number of researchers including Abo-Ghobar (1988) who looked at overland flow on a simple micro-catchment.

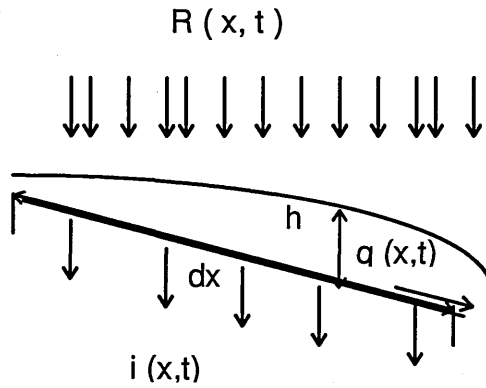


Figure 3.1 Runoff from a simple plane

3.3.1 Derivation of continuity equation

The continuity equation for a plane having one dimensional flow can be derived by considering the volume of a fluid element at a time increment (Δt) as indicated in Figure 3.2. That is:

$$(AV + Q_e(x, t)dx)dt - (A + (\frac{\partial A}{\partial x})dx)(V + (\frac{\partial V}{\partial x})dx)dt = (\frac{\partial A}{\partial t})dtdx$$

$$(Inflow) - (Outflow) = volume\ of\ element$$

3.1

Where V = flow velocity, Q_e = excess rainfall per unit width of the plane (rainfall - infiltration), $\partial A/\partial t$ = the changing rate of flow cross sectional area with time, $\partial V/\partial x$ = the changing rate of flow velocity along the plane and A is the flow cross sectional area of plane. Dividing the both sides of the above equation by $dVdt$, cancelling AV and neglecting higher order products, the equation becomes:

$$\frac{\partial A}{\partial t} + A \frac{\partial V}{\partial x} + V \frac{\partial A}{\partial x} = Q_e(x, t)$$

3.2

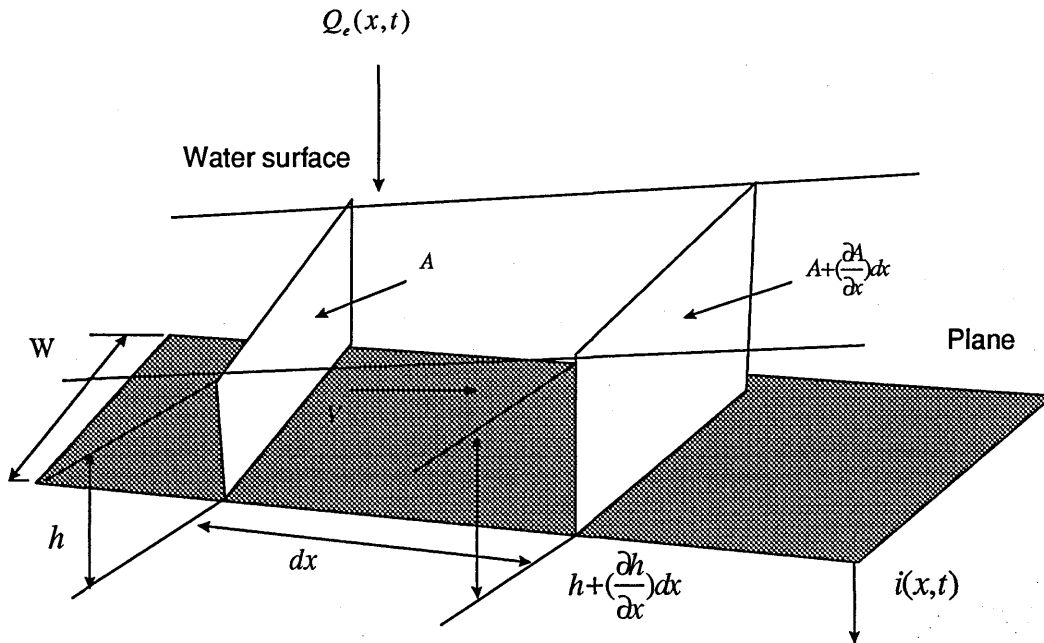


Figure 3.2 Definition sketch for continuity equation

The flow cross sectional area (A) of the plane can be written as follows:

$$A = Wh^{m'} \quad 3.3$$

Where $m' = 1$ and $W =$ the width for a rectangular shape ($A = Wh$); $m' = 2$ and $W =$ the inverse of slope ($Z = (I/S)$) for a triangle shape ($A = (I/S)h^2$) and $h =$ the depth of water. The substitution of equation (3.3) in equation (3.2) yields:

$$Wmh^{m'-1}\left(\frac{\partial h}{\partial t}\right) + Wh^{m'}\left(\frac{\partial V}{\partial x}\right) + Wm'h^{m'-1}V\frac{\partial h}{\partial x} = Q_e(x, t) \quad 3.4$$

The excess rainfall per unit width of plane is equal to rainfall, if the plane surface is impervious (i.e. $Q_e = RW$ or $Q_e = R$ where $W = 1$ and $R =$ water application rate). For a unit width of a wide plane equation (3.4) is written as

$$\left(\frac{\partial h}{\partial t}\right) + h\left(\frac{\partial V}{\partial x}\right) + V\left(\frac{\partial h}{\partial x}\right) = Q_e(x, t) = R = Q(x, t) \quad 3.5$$

Where $Q(x, t)$ is runoff rate per unit area. This equation is the result of expanding the following differential equation which was first given by Saint-Venant (Chow, 1956). This equation is the continuity equation that describes one dimensional varied flow over a surface.

$$\left(\frac{\partial h}{\partial t}\right) + \left(\frac{\partial (Vh)}{\partial x}\right) = Q(x, t) \quad 3.6$$

The term Vh is the overland flow discharge per unit width of channel (i.e. $q = Vh$). Therefore, the continuity equation can be written as follows:

$$\left(\frac{\partial h}{\partial t}\right) + \left(\frac{\partial q}{\partial x}\right) = Q(x, t) \quad 3.7$$

Where q = the overland discharge per unit width at any section of plane. The factor $Q(x, t)$ is excess rainfall which can be obtained from following formula:

$$Q(x, t) = R(x, t) - i \quad R > i \quad 3.8$$

In which $R(x, t)$ = the water application rate during an irrigation or a rainfall and i = the infiltration rate. For the simplification of analysis, $R(x, t)$ can be assumed to be constant. If the soil surface is not smooth, some of the excess rainfall will be held in depression storage. In this case infiltration and depression storage can be calculated if the rainfall and the runoff are known i.e.

$$i + \frac{ds}{dt} = R(x, t) - Q(x, t) \quad 3.9$$

Where ds/dt = change in the depression storage with time. This method which was called "back routing" by Moore and Foster (1989) provides a good measurement of time variation in infiltration rate in field study. Especially, when soil surface is relatively smooth the depression storage is negligible and infiltration rate will be calculated easily.

For an impervious smooth surface the infiltration rate is equal zero, i.e.

$$Q(x,t) = R(x,t) \quad 3.10$$

This equation also describes a steady state condition where the pervious surface is saturated and rainfall excess is equal to application rate (Henderson 1966 and Foster et al 1968). In this model R and i are assumed to be constant over whole catchment area.

3.3.2 Derivation of momentum equation

To derive the momentum equation for overland flow an element of fluid is considered. Then Newton's second law equation (Kibler and Woolhiser, 1970) or shear stress equation (Henderson 1966) is written for the forces acting in the x direction, where x is measured downstream. The following forces act on the fluid elements in x direction:

- (i) Weight of water component in downstream direction
- (ii) Hydrostatic pressure force acting at the centroid of sections.
- (iii) The friction force acting against fluid movement.

These forces can be combined to determine the general form of momentum equation for one dimensional spatially varied flow as follows (for more detail refer to Henderson 1966; Kibler and Woolhiser 1970).

$$S_f = S_o - \frac{\partial h}{\partial x} - \left(\frac{V}{g}\right)\left(\frac{\partial V}{\partial x}\right) - \left(\frac{1}{g}\right)\left(\frac{\partial V}{\partial t}\right) \quad 3.11$$

where S_f = energy slope, S_o = the bed slope of plane, h = local water depth, V = the average of water velocity, g = gravity acceleration and x = flow direction axis. Saint Venant equations (3.6 and 3.11) are true only when :

- 1- The pressure distribution is hydrostatic.
- 2- The vertical components of velocity and acceleration are negligible in comparison with components along x direction.
- 3- Momentum and energy coefficients, used as correction factors to nonuniform velocity distribution, are equal to one.
- 4- Frictional resistance in both non-steady and uniform flow is the same, so that S_f can be obtained by Manning, Chezy or Darcy-Weisbach formulae.

Woolhiser and Liggett (1967), Langford (1975) and Huggins et al (1982) assessed the effect of neglecting the dynamic and diffusion wave terms in the momentum equation (3.11) of complete model and hence established the limit of applicability of kinematic wave model by using the dimensionless number (k) defined as follows:

$$k = \frac{S_o L}{h_o F_o^2} \quad 3.12$$

in which the parameter S_o = the slope of plane, L = the length of plane, F_o = Froude number at the end of plane, h_o = the depth of overland flow at the end of plane. They stated that when $k = 0$ the maximum error in discharge hydrograph would be less than 10 percent and for values of k larger than 10, very little advantage in accuracy is achieved by using the Saint Venant

equations (3.6 and 3.11) instead of the kinematic wave equation (combination of 3.6 and 3.11 excluding dynamic terms in 3.11). Since k is greater than 10 for almost all overland flow conditions the kinematic wave equations provide enough representation of the overland flow hydrograph. The kinematic equations do not include Froude number and also neglect the changes in water surface profile due to dynamic effects. These equations only include the surface changes in the supply rate in a downstream direction.

Daniel et al(1995) also evaluated the equation (3.11) against experimental data collected in field. They found that the second, third and fourth terms were quite small in comparison with the first term, so that these could be negligible. According to them the kinematic wave equation is independent of downstream conditions but is influenced by upstream conditions. In other words the dynamic approach is unnecessary and second, third and fourth terms are eliminated and equation (3.11) is simplified to a formula that can be expressed by Darcy-Weisbach, Chezy or Manning's Equation. All the terms in the momentum equation, except the term involving the bed slope and friction slope are assumed to be negligible, and so the equation (3.11) becomes:

$$S_f = S_o \quad 3.13$$

If the slope is constant, the friction slope over the plane must be considered constant.

The general unit discharge-depth relationship is expressed as

$$q = \alpha h^m \quad 3.14$$

in which q = discharge per unit width, h = equivalent normal water depth, m = an exponent whose value depends on flow regime and α = a constant

depending on the slope and surface roughness. According to many investigators such as Henderson (1966), Smith and Woolhiser (1971), Huang et al (1978) and Hairsine (1992) this formula can be used for both laminar and turbulent flow. However, the magnitude of coefficients α and m depend upon the type of flow regime as follows:

1- A laminar law is used until Reynold's number (R_n) exceeds a critical value (R_{nc}). The coefficients α and m for laminar conditions are

$$\alpha = \frac{8gS}{kv} \quad m=3 \quad 3.15$$

where S_o = plane slope, g = gravitational acceleration, v = kinematic viscosity and $k= 24$ for a hydraulically smooth surface and 14000 for a rough surface such as grass surface.

2- A turbulent law is used when Reynold's number (R_n) is larger than the critical number (R_{nc}). The Manning equation is used for this purpose. The coefficient of α and m for turbulent conditions are

$$\alpha = \left(\frac{1}{n}\right)S^{1/2} \quad m = \frac{5}{3} \quad 3.16$$

The discharge-depth formulation (3.14) also allows the use of Chezy equation for turbulent flow when $m = 3/2$ and a laminar flow when $m = 3$. The equations and magnitude of α and m for turbulent and laminar flows presented in Table(3.1). It is generally accepted that the runoff flow on a plane starts as laminar flow and finally changes to turbulent flow when the Reynold's number increases. If the flow is in the range of transition, the m value is between 3 and 1 and cannot be a value fixed in advance.

Table 3.1 Four options for α and m in equation ($q = \alpha h^m$)

Flow regime	Turbulence		Laminar	
Author	Manning	Chezy	Darcy-Weisbach	Chezy
α	$(1/n)S^{1/2}$	$cS^{1/2}$	$(8gS)/kv$	cS
m	$5/3$	$3/2$	3	3
$q \text{ (m}^2\text{/hr)}$	$(1/n)S^{1/2}h^{5/3}$	$cS^{1/2}h^{3/2}$	$(8gS/kv)h^3$	cSh^3

3.4 Kinematic wave equation

Equation (3.14) is a two parameter model with two unknown parameters, α and m . The equation (3.14) can be substituted in equation (3.7) to obtain a partial differential equation with one dependent variable as follows:

$$\frac{\partial h}{\partial t} + \alpha \frac{\partial h^m}{\partial x} = Q(x,t)$$

3.17

or

$$\frac{\partial h}{\partial t} + \alpha m h^{m-1} \frac{\partial h}{\partial x} = Q(x,t)$$

3.18

This is the kinematic wave equation which is based on continuity and momentum equations. This equation is used in the OLF model and is also the basis of the KINEROS / EUROSEM model.

3.4.1 Solution of kinematic wave equation

Due to the complexity of the flow conditions, the general non-steady flow equations do not obey an exact mathematical solution. Huggins and Burney

(1982) also reported that, due to the nature of governing dynamic equations to an overland flow, no closed form solution is possible. Therefore, the numerical techniques such as characteristics and finite difference method are used to solve specific problems. For demonstration purposes these two approximate methods of solution are reviewed here: characteristic and finite difference methods.

3.4.1.1 Characteristic method

Characteristics method is in fact a method that converts the partial differential equation to ordinary equation. The later, for most practical purpose, are then solved using numerical method. To solve the equation(3.18), the simplest way is the process that leads to an explicit solution, but in the more complex cases numerical solutions can be used. Kibler (1968) solved this equation by using the method of characteristics. To follow this method, the equation(3.18) can be rewritten as

$$Q(x,t) = \frac{\partial h}{\partial t} + \alpha m h^{m-1} \left(\frac{\partial h}{\partial x} \right) \quad 3.19$$

In fact, the total changes in depth $h(x, t)$ is equal to the sum of partial changes in the depth due to distance and time respectively (Chow 1956).

$$dh = \left(\frac{\partial h}{\partial t} \right) dt + \left(\frac{\partial h}{\partial x} \right) dx \quad 3.20$$

or

$$\frac{dh}{dt} = \frac{\partial h}{\partial t} + \left(\frac{dx}{dt} \right) \left(\frac{\partial h}{\partial x} \right) \quad 3.21$$

where h is a variable that depends upon two independent variables such as x and t . The term $\partial h / \partial x$ is the slope of water surface and the term $\partial h / \partial t$ is the change of depth with respect to time. These two equations give the rate of changes of h , if x and t change simultaneously. Comparing like terms from equation (3.19) and (3.21) two ordinary differential equations can be obtained as

$$\frac{dx}{dt} = \alpha m h^{m-1} \quad 3.22$$

$$\frac{dh}{dt} = Q(x, t) \quad 3.23$$

These are known as the characteristic equations of equation (3.7). Therefore $h(t)$ can be calculated as follows:

$$h(t) = \int_0^{t_c} Q(t) dt \quad t \leq t_c \quad 3.24$$

and $x(t)$ will be

$$x(t) = \int_0^{t_c} \alpha h^m(t) dt \quad t \leq t_c \quad 3.25$$

The time in which outflow is measured at the end of plane is called characteristic time (t_c). Thus the local inflow at the end of plane is equal to the outflow from catchment. Depths of flow along slope and roughness coefficient can be found by using equations (3.24), (3.25) and data (runoff rate and time) collected in the field.

3.4.1.2 Finite difference method

Figure 3.3 shows a definition sketch of non-steady varied flow on a plane which is divided into reaches of finite length, Δx . The changes in the flow depth and the flow rate are assumed to be happening in time interval, Δt . For a given reach, the following notation for non-steady flow condition is considered. This procedure is similar to that of Brakensiek (1967-a). The partial changes in depth of flow due to time are

$$\frac{\partial h}{\partial t} = \left(\frac{1}{2}\right) \left[\frac{h_2 - h_1}{\Delta t} + \frac{h_4 - h_3}{\Delta t} \right] = \frac{(h_2 - h_1 + h_4 - h_3)}{2\Delta t} \quad 3.26$$

The partial changes in local flow rate per unit width due to distance are.

$$\frac{\partial q}{\partial x} = \left(\frac{q_4 - q_2}{\Delta x} \right) \quad 3.27$$

Subscripts (1, 3) and (2, 4) are the upstream and downstream parameters at initial and after Δt states respectively. The total changes are the summation of equations (3.26) and (3.27) is:

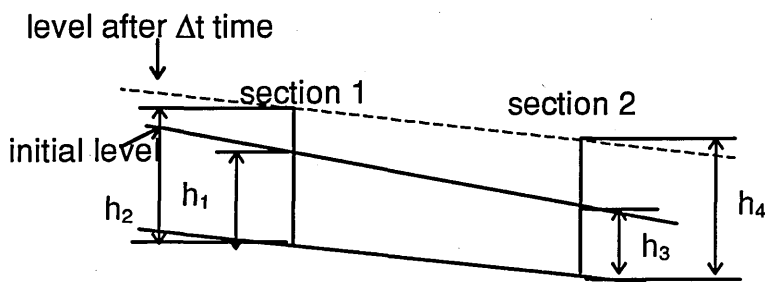


Figure 3.3 Definition sketch of unsteady varied flow.

$$\frac{\partial q}{\partial x} + \frac{\partial h}{\partial t} = \left[\frac{(q_4 - q_2)}{\Delta x} + \frac{(h_2 - h_1 + h_4 - h_3)}{2\Delta t} \right] = Q(x, t) = (R - i) \quad 3.28$$

After the substitution of equation (3.14) in (3.28), the following equation which has one unknown parameter will be obtained.

$$2\alpha\Delta t h_4^m + \Delta x h_4 - [2\Delta t \Delta x (R - i) + 2\Delta t (\alpha h_2^m) + \Delta x (h_1 + h_3 - h_2)] = 0.0 \quad 3.29$$

Equations 3.29 has to be solved for h_4 iteratively, and then corresponding Q can be then calculated by substituting h_4 in equation (3.14). In a given problem the values of h_1 , h_2 , and h_3 , were known from previous computation. Then an implicit finite equation is approximated based on a rectangular point array (Figure 3.4).

Depending on the flow regime, the α and m in the equation (3.29) can be substituted by any of the formula described in Table 3.1. For example, assuming a turbulent flow and applying the Manning's formula, the values of α and m will be

$$\alpha = \left(\frac{1}{n}\right) S^{1/2}, \quad m = 1.67 \quad 3.30$$

The following notations are used to represent the terms in equation (3.29).

$$A = 2\alpha\Delta t \quad 3.31$$

$$B = \Delta x \quad 3.32$$

$$P = 2\Delta t \Delta x (R - i) + 2\Delta t (\alpha h_2^m) + \Delta x (h_1 + h_3 - h_2) \quad 3.33$$

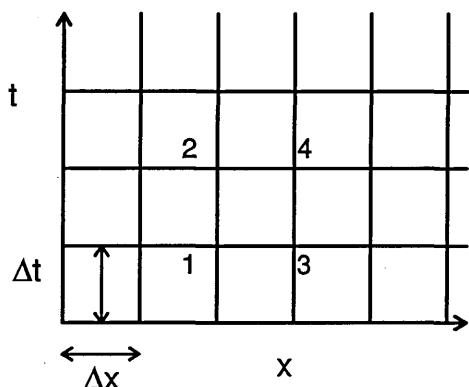


Figure 3.4 Rectangular grid for solving the finite difference equation.

The substitution of A , B , and P in equation (3.29) results

$$Ah_4^m + Bh_4 - P = 0.0 \cong F \quad 3.34$$

This is the general equation which must be solved simultaneously with equation (3.14) to find runoff rate with respect to time and distance. Initial condition is

$$h(x,0) = 0.0 \quad 3.35$$

The upstream condition is

$$h(0,t) = 0.0 \quad 3.36$$

Applying the initial and the boundary conditions to equation (3.29) gives

$$2\alpha\Delta th_4^m + \Delta xh_4 - 2\Delta t\Delta x(R - i) = 0.0 \cong F \quad 3.37$$

This equation is a simplified version of equation (3.29) and it is applicable only to the $j = 1$ and $k = 1$ node, where j is time to index and k is space index.

This is similar to Abo-Ghobar's equation (1988). These formulae (3.29 and 3.37) can be solved by using Newton-Raphson method which is well suited to solution by computer. This method is an iteration method for solving implicit equations such as (equation 2.37). The idea is that the graph of equation is approximated by a suitable tangent and using a value obtained from the intersection of tangent line and x-axis. This procedure is used for several times in a computer program to find the real root of equation by using the following relationship

$$h_4(j+1) = h_4(j) - \frac{F}{F'} \quad 3.37(1)$$

where F' is the first derivative of equation (3.37). This technique makes convergence much more rapid. It was decided that this approach was most suitable for solution of runoff problems for micro-catchments. Other investigators have shown that this type of numerical solution was highly sensitive to time (Δt) and distance increments (Δx). Foster (1968) reported that the choices of $\Delta x = 0.5$ ft and $\Delta t = 3$ seconds gave a good accuracy for unknown variables. Abo-Ghobar(1988) suggested 0.5 m and 4 seconds for high application rates and 0.5m and 8 seconds for low application rates to be used in study for soil not exposed to irrigation. He also reported that $\Delta x = 0.5$ m; $\Delta t = 0.95$ and 0.24 seconds for low and high application rate respectively gave a good result for a soil exposed to several irrigation. Morgan (1994) recommended one minute successive time steps. The $\Delta x = 0.5$ m and $\Delta t = 0.5$ minutes were chosen for this study and details are discussed further in Chapter 4.

According to Foster (1968) the coefficient of the friction includes the effects of flow channelisation, friction drag between water and soil surface, obstacles such as plant residue, vegetation, soil peaks and soil ridges, variation in local

flow regime, raindrop impact turbulence and finally detachment and transport of soil particles. The Manning coefficient which is a representative of the above mentioned factors was estimated 0.03 for a bare soil to be used in this study. This was selected using data collected in the field and comparing to standard tables and figures in literature.

3.5 Infiltration equation

Among the available empirical, physical and numerical techniques to deal with the problem of infiltration rate, the Kostiakov's equation is the most popular one. This is because this approach is more practical in field work and it is relatively easy to find the constants. As described in section 2.5, this equation takes the following form:

$$i = at^b \quad 3.38$$

in which i = instantaneous infiltration rate, t = elapsed time from the beginning of infiltration. The factors a and b are the constants that describe the soil characteristics. This equation was modified by researchers such as Kincaid (1969) and Fok (1985) to fit it for long time infiltration and infiltration under sprinkler irrigation conditions as follows:

$$i = at^b + c \quad 3.39$$

The constant c describes the final infiltration rate. According to many researchers (Kincaid 1969, Fok 1985 and Abo-Ghobar 1988) although this equation was derived for flood irrigation conditions, it is also

suitable for sprinkler). This is why this equation was selected to simulate the infiltration rate in this model.

3.6 Model development for a ridge and furrow cultivation

The previous section described the way in which the kinematic wave theory can be used to determine overland flow (runoff) for a simple plane. This section describes how this simple plane idea can be adapted to ridge and furrow cultivation as a typical agricultural micro-catchment.

3.6.1 Kinematic cascade

As discussed in section (2.10), because of the spatial variation of factors affecting overland flow and erosion, lumped models which treat an area as a single unit are not suitable. Therefore, Kibler and Woolhiser (1970); Smith and Woolhiser (1971); Kibler and Woolhiser (1972) presented a distributed hydrologic model, also called kinematic cascade, in which an area is divided into sub-areas or elements, each having special uniform characteristics of slope, soil type and land cover. The elements are arranged in a sequence to form a cascade through which water and sediment move from the top to the bottom of the hillsides and from upstream to the downstream of the channel (Figure 3.5). In other words, the kinematic cascade is defined as a sequence of a number of distinct runoff flow planes or channel reaches in which the kinematic wave equations are used to describe the non-steady flow. Langford (1975) described different catchments which could be arranged as a kinematic cascade such as, concave and convex surfaces, V-shaped and segment of a cone. He also reported the existence of discontinuity and errors arising in the water surface at each break in slope. He also showed that there are shocks in velocity and acceleration at the breaks, if the slope of planes decrease in the direction of flow. If kinematic shocks are available, the method of

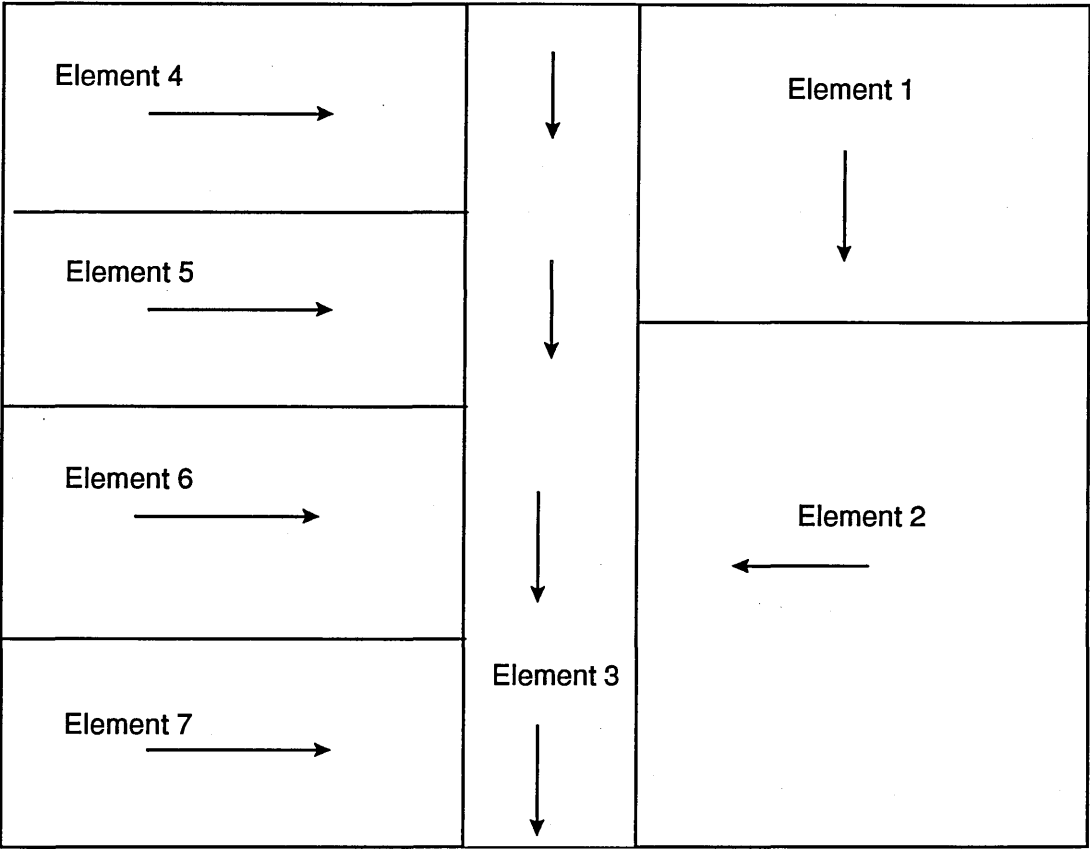


Figure 3.5 Division of a catchment into elements

characteristics is the only method to solve the kinematic wave equation. This section describes how this cascade approach can be applied to the ridge and furrow cultivation system.

3.6.2 Application of kinematic theory to a cascade

Runoff flow over elements of a kinematic cascade follows the kinematic theory equations. However, water depth at upstream boundary must be specified. If an element is at the highest position, the suitable boundary condition is

$$h(0,t) = 0.0$$

3.40

If another element is contributing runoff to the upper boundary of an element in question (as indicated in Figure 3.6), the boundary condition can be determined as follows:

$$q_{sd} = \alpha_s h_s^m(L, t) W_s \quad 3.41$$

$$q_{bd} = \alpha h^m(0, t) W \quad 3.42$$

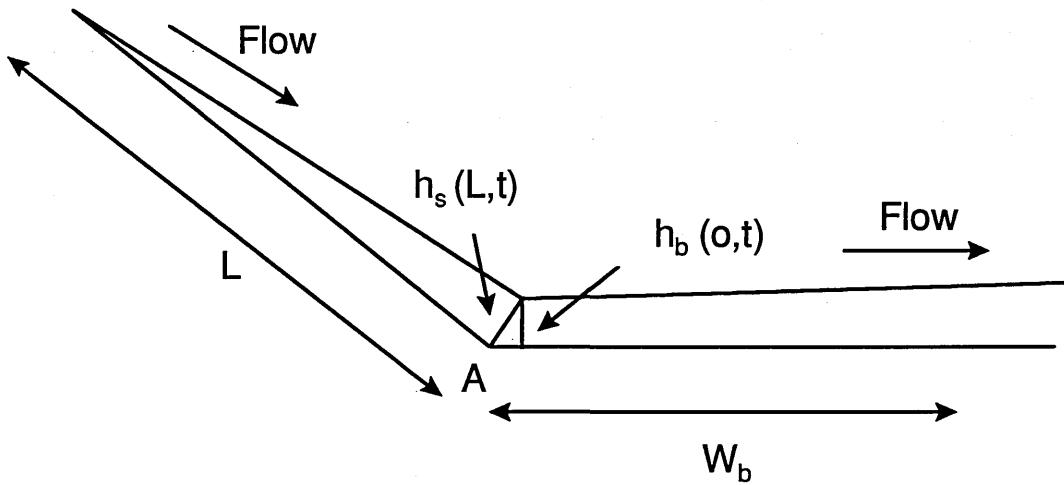


Figure 3.6 Longitudinal section of a cascade and boundary conditions.

where (q_{sd}, q_{bd}) , (α_s, α) , (h_s, h) and (W_s, W) are water runoff rates, hydraulic roughness, water depths and the widths of upper and lower elements respectively. At the conjunction point (A) the outflow from contributing element is equal to the inflow to receiving element ($q_s = q$), i.e.

$$\alpha_s h_s^m(L, t) W_s = \alpha h^m(0, t) W \quad 3.43$$

or

$$h(0, t) = \left[\frac{\alpha_s h_s^m(L, t) W_s}{\alpha W} \right]^{1/m} \quad 3.44$$

This is the boundary condition for the receiving element.

3.6.3 Application to a ridge and furrow cultivation

Figure 3.7 shows a schematic of overland flow in ridge and furrow cultivation. It is like a kinematic cascade that comprises two planes from which the runoff can develop during the application of irrigation water. The runoff collects in the bottom of the furrow and then flows down the furrow. Infiltration occurs on both the planes and in the bed of furrow. Equation (3.7) can be rewritten for this situation which consists of three simple planes or elements as follows. The continuity equation for each side of the furrow is:

$$\frac{\partial q_s}{\partial x} + \frac{\partial h_s}{\partial t} = Q_s(x, t) \quad 3.45$$

The continuity equation for the furrow bed is:

$$\frac{\partial q_b}{\partial x} + \frac{\partial h_b}{\partial t} = Q_b(x, t) + \frac{2Q_s}{W_b} \quad 3.46$$

So the total lateral flow to the bed (Q_t) is:

$$Q_t = Q_b + \frac{2Q_s}{W_b} = (R - i_b) + \frac{2}{W_b}(R - i_s) \quad 3.47$$

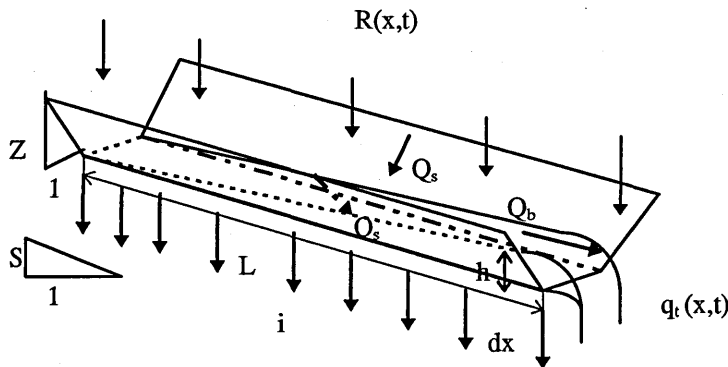


Figure 3.7 Runoff from ridge and furrow cultivation.

where q_s and q_b = the flow rate per unit width of sides and furrow bed element, (Q_s and Q_b) = lateral flow from sides and bed, Q_t = total lateral flow to the bed of each micro-element and h_s and h_b = the equivalent water depth for runoff from sides and bed.

So the overland flow from the sides and the bed of a ridge and furrow is spatially varied flow and has the same form as equation (3.7). The total discharge is the sum of runoff from the bed and two sides of the furrow (i.e. $(2Q_s/W_b + Q_b)$). Therefore, the kinematic wave equation for a ridge and furrow will be

$$2\Delta t q_4 + \Delta x h_4 - [2\Delta t \Delta x (R_b - i_b + 2Q_s/W_b) + 2\Delta t (\alpha h_2^m) + \Delta x (h_1 + h_3 - h_2)] = 0.0 \quad 3.48$$

Substitution of equation 3.14 in equation 3.48 results in:

$$2\alpha_b \Delta t (h_4^m) + \Delta x h_4 - [2\Delta t \Delta x (R_b - i_b + 2Q_s/W_b) + 2\Delta t (\alpha h_2^m) + \Delta x (h_1 + h_3 - h_2)] = 0.0 \quad 3.49$$

This is the kinematic wave equation for ridge and furrow cultivation. Where W_b = the width of furrow bed and $R_b - i_b = Q_b$ = total lateral flow to the bed from both excess rainfall and the previous micro-element. Using the following notation:

$$A = 2\alpha_b \Delta t \quad 3.50$$

$$B = \Delta x$$

$$P' = 2\Delta t \Delta x (R_b - i_b + 2Q_s/W_b) + 2\Delta t (\alpha h_2^m) + \Delta x (h_1 + h_3 - h_2) \quad 3.51$$

The values of α for the sides and the bed of the furrow can be calculated as follows:

$$\alpha_s = \left(\frac{1}{n}\right)(S_s)^{1/2} \quad m = 1.67 \quad 3.52$$

$$\alpha_b = \left(\frac{1}{n}\right)(S_b)^{1/2} \quad m = 1.67 \quad 3.53$$

where S_b and S_s = bed slope and the furrow side slopes. After the substitution of terms A, B and P' into 3.49 and simplification, the following equation is obtained for the first grid:

$$A(h_4)^m + B(h_4) - P' = 0.0 \equiv F \quad 3.54$$

This equation together with equations (3.14) and 3.50 to 3.53 can be used to predict runoff from a ridge and furrow catchment, assuming similar application and infiltration rates for both sides and bed. The infiltration rate assumption is quite reasonable for the irrigations followed by the first irrigation. This is because the deposition of sediments washed during the first irrigation blocks the soil surface porosity and retards the infiltration rate in the bed as low as that of the sides during the following irrigation. Overall, steep side slopes cause low infiltration rates and deposition of sediments washed from the sides causes low infiltration rate in the bed. Therefore, the assumption of the similarity of infiltration rate in the bed and the sides can be reasonable.

3.7 Model development for stationary sprinklers conditions

When the sprinkler systems apply water without moving the situation is expected to be stationary condition. When a catchment is irrigated by stationary sprinklers, it is assumed that the whole area is wetted simultaneously. The time to apply water and the time to stop are the same for whole area, even if the receiving area has been divided into different elements. In this case each element in the catchment must be assigned to one rain gauge. For stationary condition, the record of one water application gauge or the average of the few of them can be used for a catchment. The application rate for this condition can be determined as follows (ISO 7749-1 1995):

$$R = \frac{60 \times 10 \times V_v}{a \times t} \quad 3.55$$

In which R = application rate (mm/hr), V_v = the volume of water in water application gauge (cm^3), 60×10 = conversion factor, a = water application gauge area (cm^2) and t = application time (s). One of the main input parameters to the model is water application rate and for sprinkler irrigation this can come for stationary or moving sprinklers.

Overall, the models developed for a simple plane and a ridge and furrow catchment can simulate runoff from sprinkler irrigation systems in a stationary condition, even if the catchment is divided into a number of elements of different characteristics. In the last case, the kinematic cascade can be applied.

3.8 Model development for moving sprinklers

Developing a lumped model for moving sprinklers needs to consider some factors such as travel speed, application time and nozzle discharge. When it is dealing with a distributed single event model the catchment should be divided into elements in order to simulate the moving condition. In the following sections these cases are discussed. In this case the application rate is assumed to be constant over the entire wetted area.

3.8.1 Travel speed and application rate

For moving sprinklers, the application rate is unaffected by speed of the sprinkler. However, the application depth is a function of travel speed and so it should be chosen so that the design application depth is applied. The following equation describes the relationship between depth of applied water and travel speed (Keller, 1990):

$$d = \frac{1000 \times Q_n}{V \times w} \quad 3.56$$

in which d = depth of applied water (mm), V = travel speed (m/hr), w = towpath spacing (m) and Q_n = nozzle discharge (m³/hr). The water application rate for a moving sprinkler can be determined as

$$R = \frac{6 \times 10^4 \times Q_n}{t \times w \times V} \quad 3.57$$

where R = water application rate (mm/hr) and t = water application time (hr). This equation can be used in equations (3.29) and (3.49) to predict runoff from a simple plane and a ridge and furrow catchment in moving sprinkler irrigation conditions.

3.8.2 Travel speed and runoff

There is an inverse relationship between water application depth and travel speed (equation 3.56) and a direct relationship between runoff and application depth. At a constant application rate, while the travel speed increases, water application depth and hence produced runoff depth starts to decline. The relationship between runoff and depth of application water is:

$$d = \frac{d_r}{C_o} \quad 3.58$$

or

$$d_r = C_o \times d \quad 3.59$$

in which d_r = runoff depth, C_o = runoff coefficient and d = the gross depth of water application. If the equation (3.56) is substituted in equation (3.58), the following formula can be obtained:

$$d_r = C_o \times \frac{1000 \times Q_n}{V \times w} \quad 3.60$$

where V = travel speed (m/hr), w = towpath spacing (m) and Q_n = nozzle discharge (m³/hr). This formula can describe the relationship between runoff and travel speed. When the travel speed is low, both the water application depth over the catchment and runoff from the catchment will be high. The equation 3.60 is a lumped model. This model can roughly simulate runoff from a simple plane or ridge and furrow.

3.9 Comparison between simple plane; ridge and furrow

So far two different model applications have been considered, one for a simple plane and another for a ridge and furrow. This section examines the effect of treating the ridge and furrow catchment as one single plane rather than three separate planes to see what effect this would have. If the kinematic equation for the simple plane (3.37) is subtracted from kinematic equation for the ridge and furrow (3.49) and ignoring the difference in runoff depths on sides and beds for the first grid, the result is as follows:

$$i_p = i_f + \frac{2Q_s}{W_f} = i_f + \frac{2}{W_b}(R - i_s) \quad 3.61$$

Where i_p and i_f = the average infiltration rates for a single plane and the sides and the bed of a ridge and furrow together, Q_s = lateral flow from furrow side and W_b = width of furrow. According to this equation the infiltration rate for the bed (simple plane) is more than the infiltration rate for the ridge sides (ridge and furrow). When the side slope increases and the width for the bed reduces the second term on the right hand side of equation (3.61) increases. This leads to an increasing infiltration rate for the furrow bed. So the steeper the side slope, the lower the infiltration rate and the more the runoff generated

from the side. The next point is the short length of side compared to bed length so that the water traveling time on the side becomes shorter than those of bed. Therefore, the chance for water penetration on the side is less than on the bed.

Anyway, the significant of the potential runoff from a ridge and furrow depends on the width and slopes of sides and bed. If the furrow side slope increases the infiltration rate will reduce. Accordingly, the runoff from a ridge and furrow catchment under sprinkler irrigation conditions is more than runoff from a simple plane. Therefore, the simple plane model will underestimate the potential runoff from a ridge and furrow cultivation practices.

3.10 Comparison between stationary and moving sprinklers

The model can be applied to sprinkler systems in either stationary or moving conditions. Although the travel speed is an index to moving sprinklers, it does affect water application rate. So if the kinematic equation derived for a simple plane (3.34) (or a ridge and furrow (3.54)) under moving conditions is subtracted from that of under stationary conditions and ignoring the difference in runoff depth for stationary and moving conditions for the first grid, the result will be as follows:

$$P_s - P_m = 0.0 \quad 3.62$$

Where P_s and P_m are the values of term (3.33) or (3.51) for stationary and moving conditions. If these two equations are substituted in equation (3.62), the result for the first grid will be

$$2\Delta x \Delta t (R - i - R' + i') = 0.0 \quad 3.63$$

or

$$i = i' \quad 3.64$$

This means when water application rates are equal, the infiltration rates for moving and stationary conditions are equal as well. Accordingly, there will be no difference in the amounts of runoff from a simple plane (or from a ridge and furrow) under stationary and moving conditions having the same catchment area.

3.11 Model operation

In order to evaluate the runoff model (OLF) a computer program was written in Quick Basic which is compatible with any IBM computer programming. This program is for both a simple plane and a ridge and furrow. A flow chart of this program is presented in Figure.3.8. A full list copy of this program is presented in Appendix A.1.

The program starts by taking a constant value of water application rate, catchment geometry parameters, time and distance increments; initial soil water content and infiltration constants. Then it computes the infiltration rates with respect to time and finds the rainfall excess at the end of each distance increment and at the end of catchment using four points finite difference method. Initial and boundary conditions of the sides of a ridge and furrow are zero for all the grids at the beginning of irrigation and along the sides. After each time increment the lateral flow from two sides is added to that from bed and the new depths of runoff are computed along the bed at each place. The program continues for total runoff duration and for whole length of simple plane or both sides and the bed of a ridge and furrow and finally the runoff depth and runoff flow per unit width are determined at the end of catchment.

The depth of runoff (the zero roots of implicit equation) is calculated using Newton-Raphson's method. Features that can easily be changed in program input file are water application rate, catchment characteristics, infiltration constants, soil water content and roughness coefficients. The time required to run the program depends on the water application time, and the increments of time and distance.

3.11.1 Input and output data

The input data to the OLF model are tabulated in Table (3.2). Depending on the type of catchment (simple plane or ridge and furrow), the number of input data to the model is different. Some of these data are same for all the elements of a catchments (e.g. water application time) and some are different (e.g. width). Some of input parameters are difficult to be measured therefore they are assumed to be equal to the identical parameter values (e.g. bed infiltration rates and ridge infiltration rates).

The outputs are time, water application rate, runoff flow per unit width, runoff rate per unit width, runoff rate per unit area and the identification of catchment (Table 3.2).

3.12 Limitations of the OLF model

This model assumes a constant value of water application rate and computes the runoff during an event. So if the water application rate changes during one event this model will not be able to predict proper runoff. The variability of catchment characteristics such as infiltration rate and geometric dimensions such as slope are included just for three elements in this model. The capability of this model for runoff prediction under moving sprinkler irrigation is also limited.

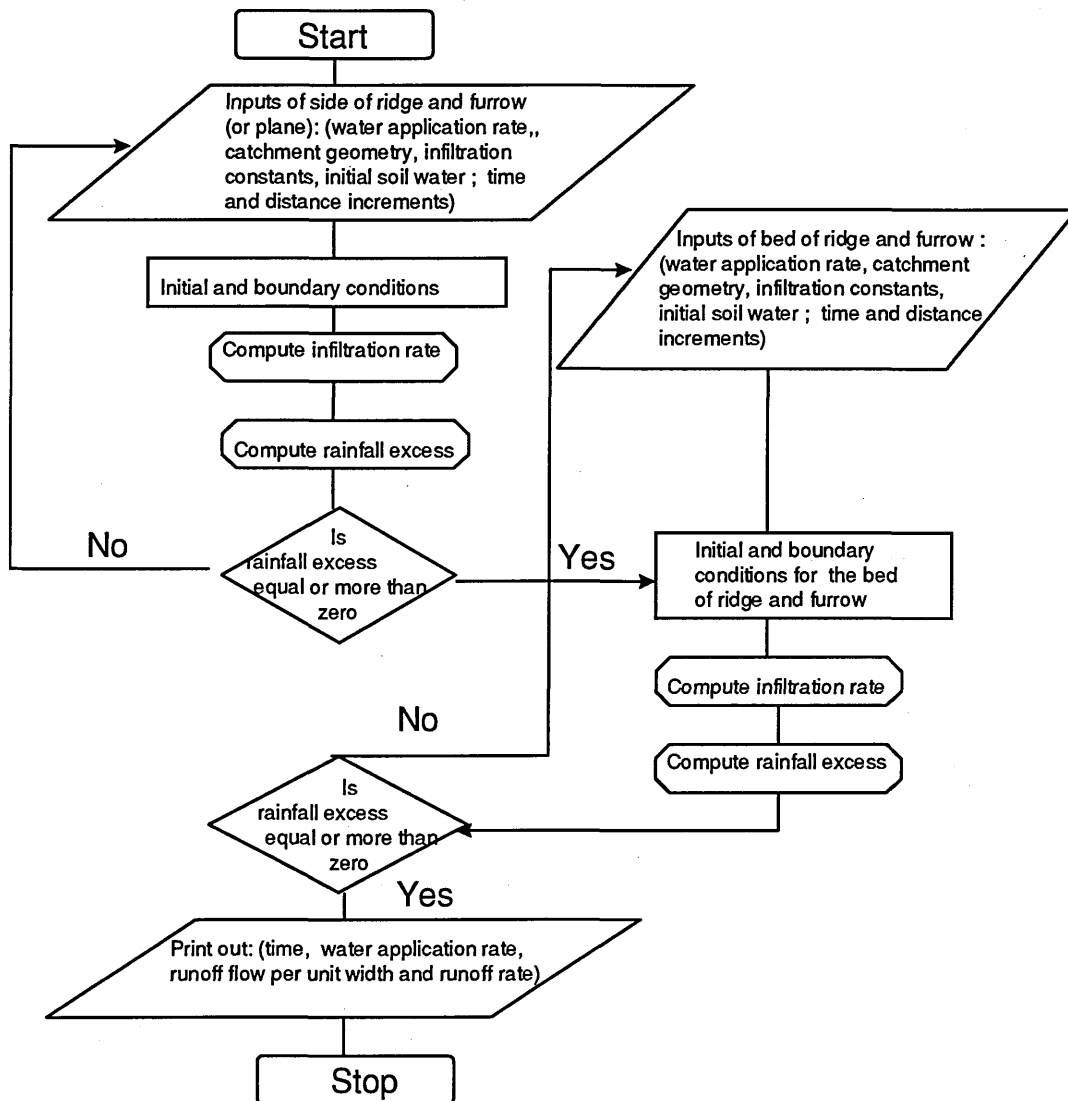


Figure 3.8 Flow chart of OLF model

Table 3.2 Input and output data to the OLF model

Parameters	Symbol	unit
Inputs:		
Water application rate	R	mm/hr
Distance increment	Deltaxb (s)	m
Time increment	DeltaT	min
Longitudinal side slope	Ss	%
Longitudinal bed slope	Sb	%
Length of furrow	Lb	m
Length of sides	Ls	m
Width of side	Ws	m
Width of furrow	Wb	m
Flow regime parameter	m	
Manning's coefficient	nb, ns	m ^{1/6}
Infiltration constants (at ^b) for bed (b) and side (s)	ab, as, bb, bs	
Water application time.	Waterapptime	min
Outputs:		
Time	T	min
Runoff depth along the slope	h	mm
Runoff flow per unit width	q	m ² /hr
Runoff rates per unit width	Q _r	mm/hr

Note: More details of input and output parameters are explained in Appendix A..2

Overall, this model is a type of semi-distributed model and cannot manipulate the local and the temporal changes in parameters during one event. To consider these changes, a more advanced and comprehensive single distributed model is required. This is why, the KINEROS modified to EUROSEM model has been selected to achieve these purposes (see section 2.10). This model is also based on the kinematic wave theory as already described, but is much more sophisticated. There are some differences between this model and KINEROS which will be discussed in the following sections.

KINEROS-EUROSEM model

The Kinematic runoff Erosion or KINEROS model is a physically distributed single event model which was developed to predict surface runoff and erosion from large hydrological catchments (Woolhiser et al, 1990). This model was adapted and modified to a new model called European Soil Erosion Model (EUROSEM) by Morgan et al (1992) to evaluate the soil erosion in European countries. In this section a short review of KINEROS modified to EUROSEM model will be discussed.

3.13 Rainfall infiltration equation

Smith (1983) reported that two parameters are the key to the infiltration model. One is the saturated hydraulic conductivity (K_s) and other is the capillary drive (G). The effective capillary drive is related to unsaturated hydraulic conductivity and matric potential as following equation:

$$G = \frac{1}{K_{sat}} \int K(\Psi) d(\Psi) \quad 3.65$$

In which K_{sat} = the saturated hydraulic conductivity, $K(\Psi)$ = unsaturated hydraulic conductivity and Ψ = matric potential. Smith and Parlange (1978) used the following relationship between the infiltration capacity, the amounts of rainfall and the soil water content as follows:

$$i_c = \frac{K_{sat} \exp(\frac{d_i}{B})}{(\exp(\frac{d_i}{B}) - 1)} \quad 3.66$$

Where i_c = the infiltration capacity of soil K_{sat} = the saturated hydraulic conductivity of soil, d_i = the amount of rain already absorbed by soil and B = the product of capillary drive by the saturated deficit of soil.

$$B = G(\theta_s - \theta_i) \quad 3.67$$

Where the B and the G have the same unit (mm). If the right side of equation (3.67) is divided and multiplied by porosity of soil (ϕ), the following equation is obtained

$$B = G\phi(S_{max} - S_i) \quad 3.68$$

Where S_{max} and S_i = the maximum and initial values of relative saturation which is defined as

$$S_{sat} = \frac{\theta}{\phi} \quad 3.69$$

The variation of S_{sat} is between 0 and 1 and it is easier to use in the model. As indicated in Figure 3.9, for a short time after the beginning of rainfall (when $d_i/B < 0.1$), the infiltration is free from gravity force effect, i.e

$$i_c = \frac{BK_s}{d_i} \quad 3.70$$

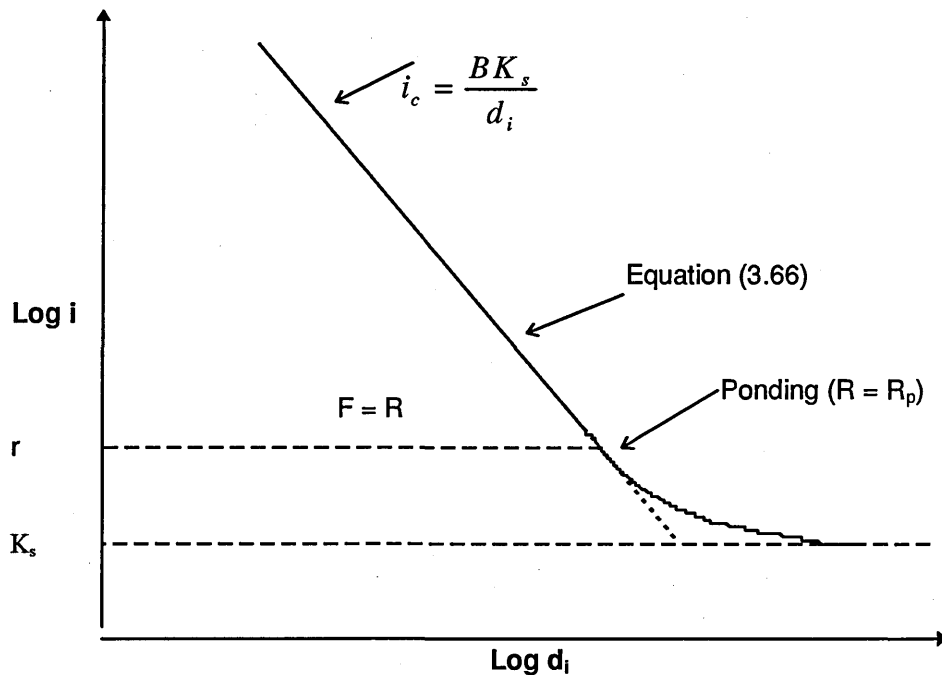


Figure 3.9 Definition sketch for infiltration model (Smith and Parlange , 1978)

At small values of d_i , the infiltration-rainfall curve (Figure 3.9) is described by equation (3.70). At large values of d_i , it is described by $i_c = K_s$.

It is difficult to find the capillary drive through unsaturated hydraulic conductivity. So Woolhiser et al (1990) recommended guide values for soil hydraulic characteristics to use as input to the KINEROS model. Morgan et al (1993) also reported those range of values for any type of soil in the EUROSEM user guides to use as input to the EUROSEM model. For this research the direct measurement of capillary drive was preferred. However, the determination of the sorptivity value is required prior to finding capillary drive. There are two options for the determination of sorptivity values:

1- The sorptivity value can be estimated from cumulative infiltration depth versus time by using Philip's equation (1969)

$$I = s_s t^{1/2} \quad 3.71$$

in which I = accumulated infiltration (m), t = elapsed time (sec) and s_s = a soil constant which is called sorptivity ($m/s^{1/2}$). A plot of cumulative infiltration versus $t^{1/2}$ will give a straight line with a slope of s_s as follows

$$s_s = \frac{1}{t^{1/2}} \quad 3.72$$

After finding the value of sorptivity, the capillary drive can be determined using following procedure which was stated by Philip (1969); White and Sully (1987) The relationship between sorptivity (s) and matric flux potential of soil (ϕ_m) is:

$$s_s = \left[\frac{(\theta_s - \theta_i) \phi_m}{b} \right]^{1/2} \quad 3.73$$

or

$$\phi_m = \frac{s_s^2 b}{(\theta_s - \theta_i)} \quad 3.74$$

where θ_i = the initial water contents of soil just before the rainfall, θ_s = the water content of soil at the saturated condition, ϕ_m = the matric flux potential of soil (m^2/sec) and b is 0.5 (dimensionless) for soils showing a step function infiltration front and to be .55 when the actual infiltration front tends not to be as sharp as a step function (Reynolds and Elrick 1990). While soil water potential at supply surface (Ψ_o) is more than the antecedent potential (Ψ_a), b is confined between 1/2 and $\pi/4$ (White and Sully, 1987). According to Gardner (1958) the parameter ϕ_m can be defined as follows:

$$\theta_m = \int_{-\infty}^0 K(\Psi) d\Psi \quad -\infty \leq \Psi \leq 0 \quad 3.75$$

The G value can be determined by using the following formula (Smith, 1983)

$$G = \phi_m / K_{sat} \quad 3.76$$

2- Alternatively, the capillary drive values can also be determined from the ponding time method which was described in section 2.5.3. In this method having two ponding time records is enough to find saturated hydraulic conductivity of a type of soil and its capillary drive.

3.14 Application to a ridge and furrow

KINEROS model was modified to simulate runoff and erosion from rill and interrill by Morgan et al (1992). The modified model called EUROSEM can be used to predict runoff from a ridge and furrow. In this model the sides of a furrow can be considered as an interrill and bed as a rill.

Alternatively, a ridge and furrow can also be considered as a catchment consisting of three simple plane (bed and two sides). This will make a cascade from which runoff can be predicted.

Due to small width of ridge and furrow catchment (around 900 mm), it is also possible to assume it as a simple plane or channel and predict runoff from it. Error arises from this assumption will be assessed in the following chapters.

3.15 Model development for moving sprinklers

In contrast to the stationary conditions, the times to apply water and the times to finish it are not the same for all the elements of a catchment under a moving sprinkler condition. Therefore, the whole irrigation area in one set is not

simultaneously under water application. Water application rates increase as an irrigation machine moves toward a point in the field and start to reduce when it passes over that point. So if a catchment, even with a non-uniform characteristics, is divided into several elements, each element may receive nearly a constant water application. In this case the time to start to apply water and time to stop it on each element will be different. Runoff from a field under moving sprinkler systems can be simulated, if the irrigated area of one set is divided into a number of elements. These elements will be irrigated at successive times to start and successive times to finish a design application depth at the specific time of application. The more the elements are, the more precisely the simulation of moving sprinkler will be. Figure 3.10 shows a water application pattern for a raingun sprinkler over a field. If this pattern repeated side by side it can simulate the patterns of other types of moving irrigators such as side move traveler.

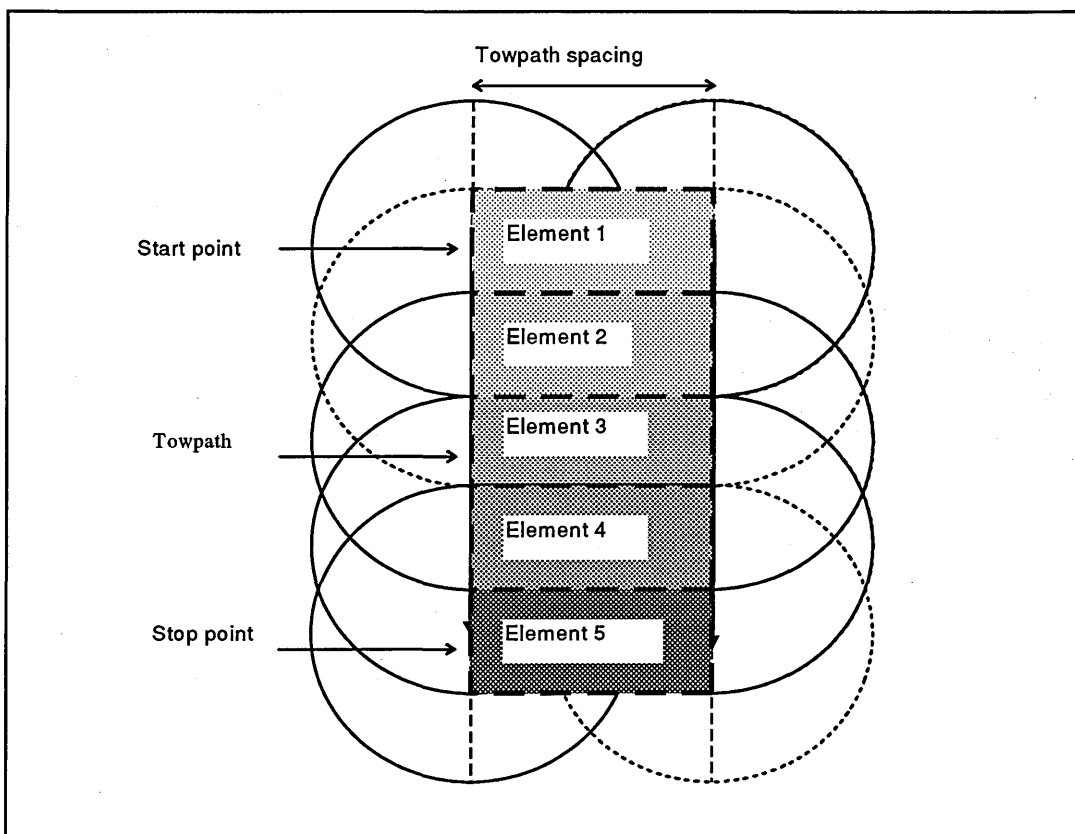


Figure 3.10 Water application patterns of a moving sprinkler over a field

3.16 Operation of KINEROS-EUROSEM model

The Kinematic Runoff Erosion model (KINEROS) is a distributed single event model. This model has been modified to the European Soil Erosion Model (EUROSEM) which was a joint effort of European scientists (Morgan et al 1993). This model was written in FORTRAN 77 and will run on any IBM compatible computer with 640 k bytes RAM using the MS-DOS operating system.

The present EUROSEM version 3 is used in this research to study surface runoff from simple planes, ridge and furrow catchment or a combination of them under stationary or moving sprinkler conditions. A flow chart of this model is presented in Figures 3.11. The model operates by taking water application rates and considering the interception of water by the plant canopy, direct throughfall, leaf drainage and stem flow and depression storage. Then the soil infiltration rate and excess rainfall are calculated. After that the runoff depth over the catchment is determined with respect to time and distance by using the finite difference solution. The Newton-Raphson method is used to solve the equation. The computation process is repeated when the input is changed. The model can predict surface runoff and soil erosion from a catchment having at most sixty elements with a variety of catchment and rainfall characteristics.

Although the purposes of this model were to simulate runoff and erosion from a single plane (or multiple planes, multiple planes and channels), this model can also predict runoff from a moving storm (personal communication with Morgan, 1996). So, it is the first time this model has been examined to predict surface runoff under moving sprinkler conditions. A flow chart of this model for moving sprinkler conditions is presented in Figure 3.12.

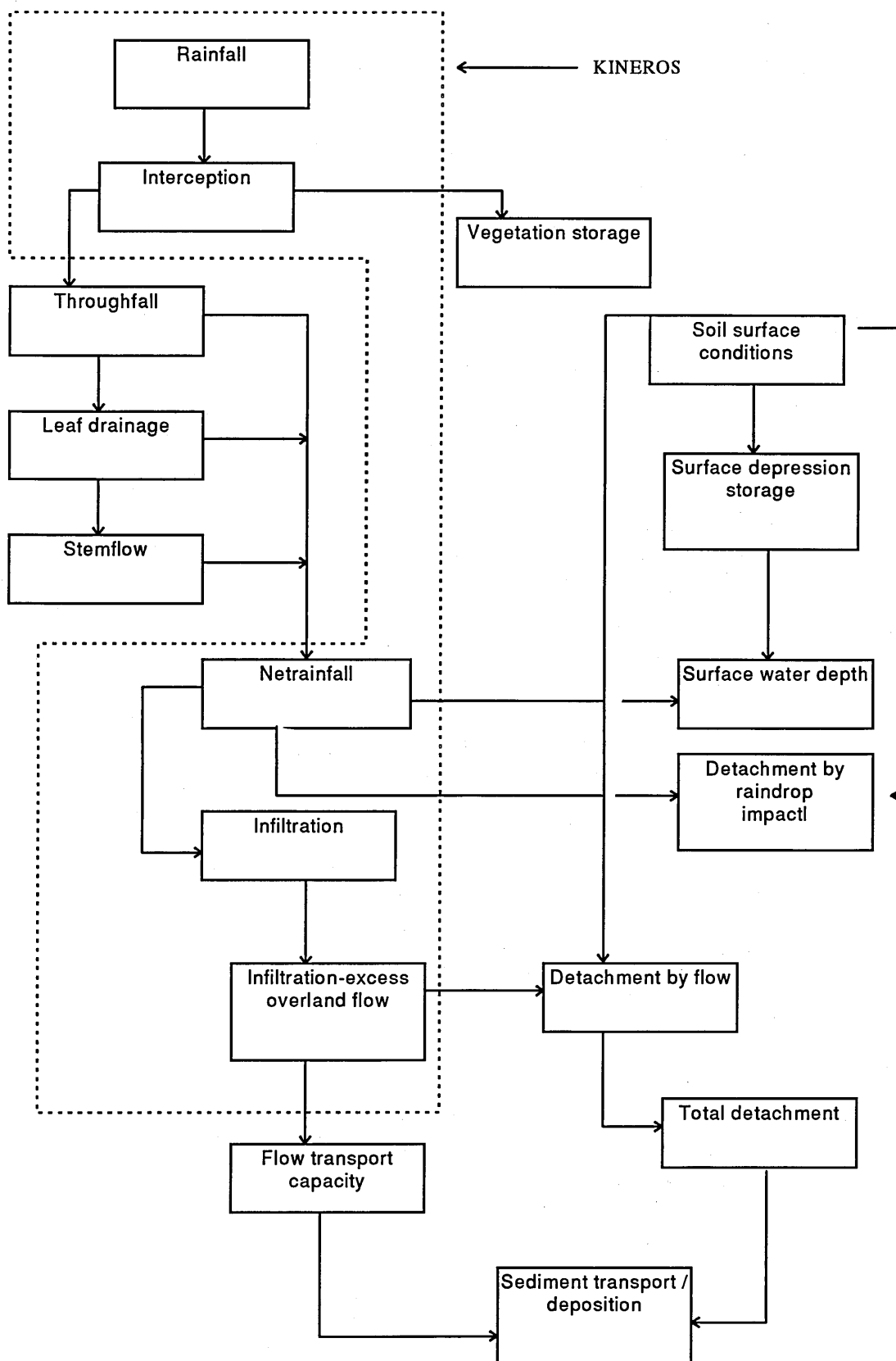


Figure 3.11 Flow chart of EUROSEM-KINEROS model.

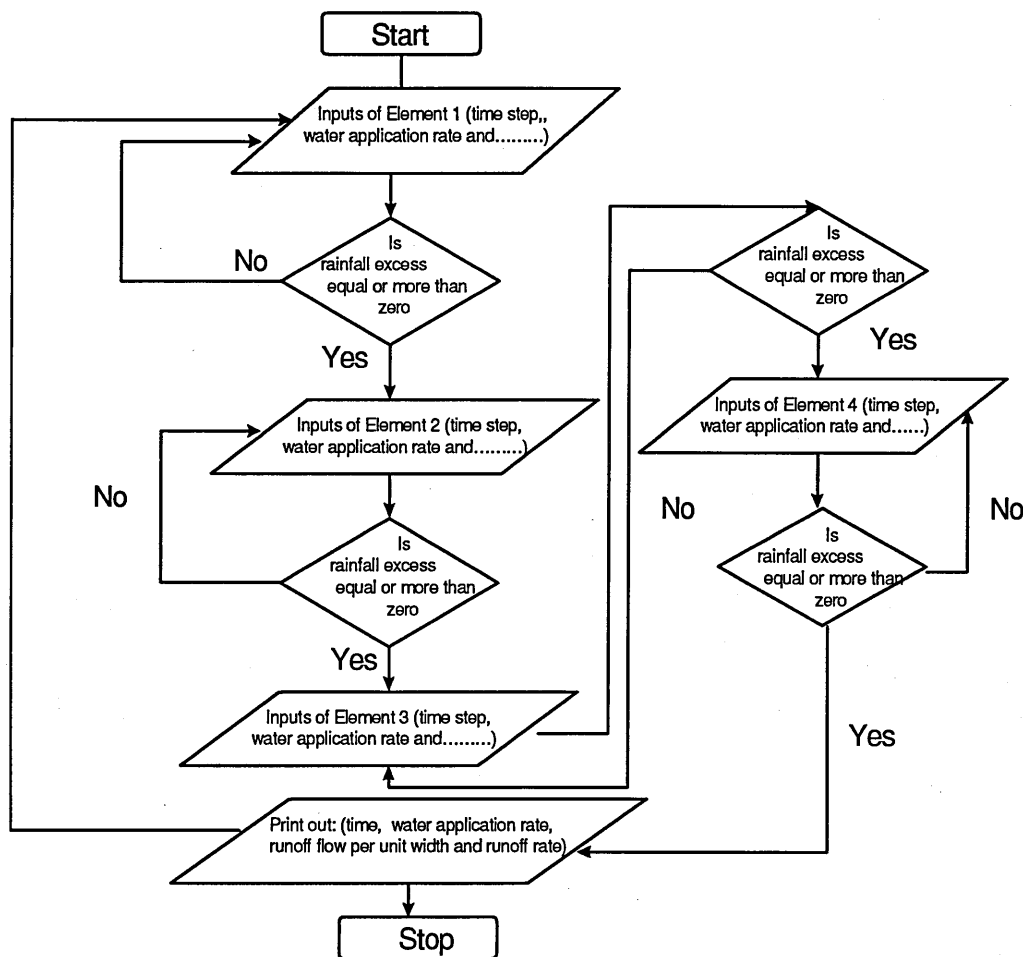


Figure 3.12 A flow diagram of KINEROS for moving sprinklers

3.16.1 Input files

EUROSEM model requires two types of inputs files such as rainfall (water application) input file and catchment input file. The rainfall input file includes accumulated depth of water, element number, rain gauge number, maximum number of time, depth pairs for gauges and the number of rain gauge. The catchment data file describes the characteristic of the catchment or elements such as catchment geometry, soil physical condition and mechanical parameters; soil surface features and configuration and vegetation characteristics (see Appendix A.2). The detail of input file parameters are

written in the EUROSEM user guide (Morgan et al,1993). Observed data file is also provided for calibration and validation purpose.

3.16.2 Output files

There are three output files provided automatically in EUROSEM version 3. These files are: dynamic file, static file and auxiliary file. Dynamic file contains some information about runoff hydrograph (such as volume of runoff, runoff depth, time to peak, time to runoff, peak runoff discharge, peak) and sedigraph (such as total sediment, sediment concentration, peak sediment discharge), rainfall intensity, area of element and water balance computation.

The static output file contains information already entered for the catchment characteristics, erosion summary, the hydrological summary of elements, rill dimension with respect to distance and global volume balance.

The auxiliary file contains information about the interception, rainfall intensity and kinetic energy of rain drops with respect to time, interrill dimensions and slopes, rill and interrill erosion, geometric parameter and water balance at the end of plane. The details of these three files are mentioned in EUROSEM user guide (Morgan et al 1993).

3.17 Conclusions

This chapter summarizes the development of a runoff model developed for a simple plane and a ridge and furrow cultivation. This model is called Overland Flow (OLF) model. Theoretically, it is similar to other available models which were discussed in section (2.10). For instance, SROFF (Abo-Ghobar 1988), the KINEROS (Woolhiser et al, 1990) modified to EUROSEM (Morgan et al 1992). Although the OLF is an advanced model when compared to SROFF

model, it is still a single event lumped model. Therefore, its capability is less than the KINEROS and the EUROSEM models that are distributed single event models. Especially, the EUROSEM is a more comprehensive model, when it is linked to the KINEROS model. In addition, the KINEROS can also simulate runoff from a moving storm as well as a moving sprinkler. EUROSEM also simulates runoff from rill and interrills and can also predict runoff from a ridge and furrow. The predicted runoff hydrographs resulted from the OLF and KINEROS-EUROSEM models are compared to the observed runoff hydrographs for simple plane and ridge and furrow in both laboratory and field experiments. The results are summarized in Appendix A.1

Overall, due to this description, the reasons already described in section (2.10) and good results taken from comparison between observed and predicted data in the following chapters, KINEROS-EUROSEM has been chosen to predict runoff under sprinkler irrigation systems in this study.

CHAPTER 4

MATERIAL AND METHODS

4. Material and methods

4.1 Introduction

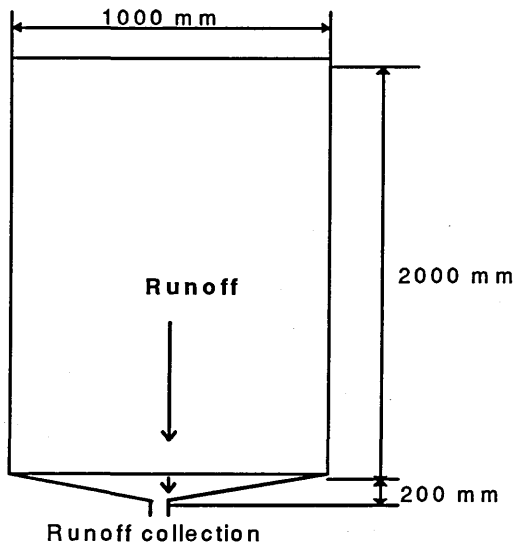
The purpose of this chapter is to describe the methods adopted to carry out laboratory experiments for the evaluation of the model developed in chapter 3.

4.2 Laboratory equipment

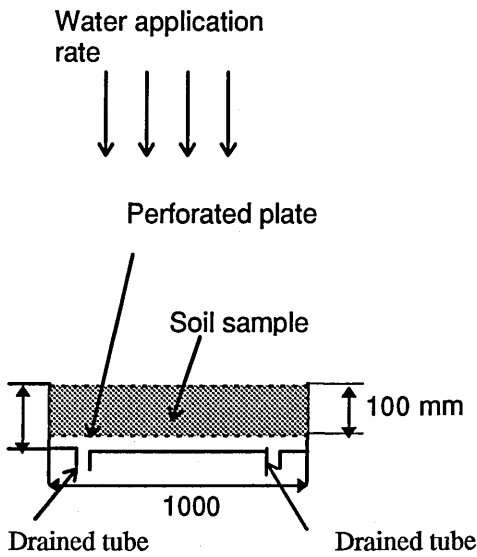
A rainfall simulator that consisted of three spray nozzles, a gauge pressure, an electric-pump and a supply hose was used to simulate the rainfall in the laboratory experiments (Figure 4.1). The three spray nozzles with the same size were spaced at the distance of 650mm apart on a bar. These parts were installed on a frame at a height of 3m to apply water. A soil tray with the dimension of 2000mm×1000mm×250mm was placed under the rainfall simulator. It consisted of a meshed metal plate, two drain tubes and a collecting box. The meshed metal plate was fixed at the height of 50mm above the tray bed (Figure 4.1-b). The two drain tubes were installed at the bottom of tray to collect the drained water in order to measure the infiltration rate. The collecting box at the outlet of the tray was used to collect runoff (Figure 4.1-a). The tray was filled with a sandy loam soil sample with the thickness of 100 mm. The whole system was put on a platform whose slope could be changed (Figure 4.1-d and c).

4.3 Preliminary tests

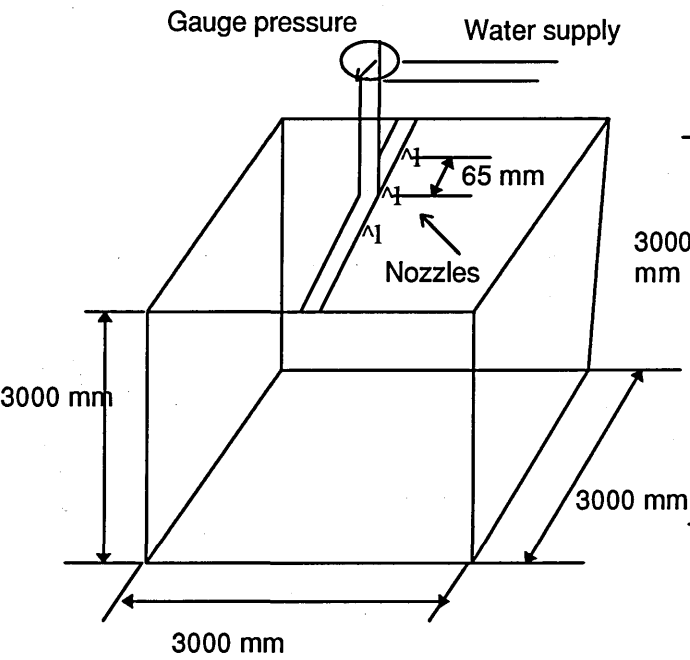
Before doing the main experiments, preliminary tests were carried out to set up the rainfall simulator properly in the laboratory. These included the selection of the number and size of nozzles, measurement of uniformity



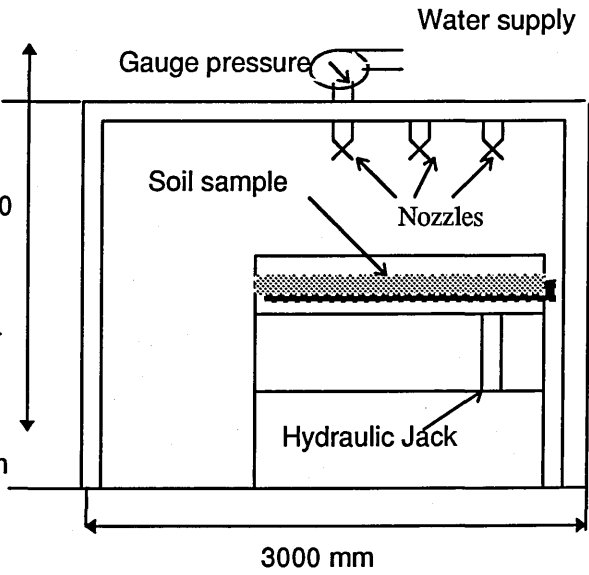
(a)- Simple plane



(b)- Cross section of soil tray



(c) Rainfall simulator



(d) Cross section of rainfall simulator.

Figure 4.1 Rainfall simulator and soil tray

coefficients, measurement of application rates and assessment of the influence of some of the main factors which influence the runoff hydrograph. In addition to these, some factors such as soil particle size distribution, roughness coefficient, hydraulic conductivity and capillary drive which were also measured in the laboratory are described in this section.

4.3.1 Water application rate tests

Water application rate is the intensity of water applied per unit time per unit area. This parameter should be measured as accurately as possible. In the laboratory the application rate was measured using three methods for different soil surface slopes and results were compared with the results for zero slope.

In the first method a grid of catch cans was used to collect the applied water and then the average volume was calculated. After that the average water application rate was computed by using the average volume, application time and catch area (see section 3.7) (Tables 4.1 & 4.2).

In the second method a polythene sheet was used to cover the whole catchment. Then the applied water was collected in a bucket and measured with respect to time. This method gives the average depth of rainfall on the whole catchment. In the third method, the drained water was measured volumetrically at the end of each test. After that the application rate was calculated by applying the water balance equation. The values obtained using the three methods gave very similar results and the average was used for simulation purposes (see Tables 4.1 & 4.2).

The water application test is affected by many factors such as water pressure, nozzle spacing, uniformity distribution, land slope and method of measurement (see section 2.6). To optimize these factors the following tests were undertaken.

Table 4.1 Water application rate measurements (system pressure = 1.5 bar).

Nozzle size (mm)	Ridge and furrow tests	Test No.	Soil slope (%)	Application		Soil water content (%) (by volume)	Coefficient of uniformity (%)	Time interval (hr) ¹	Basic infiltration rate (mm/hr)	
				1- can	2- tray				Observed ²	Calculated ³
3	Ridg1	1	3.5	63	60	31	88	1.5		50
"	Ridg2	2	16.5	66	58	30	89	2.5		43
"	Ridg3	3	23.5	60	61	26.3	88.4	90		53
"	Ridg4	4	23.5	59.5	61	31.7	88.4	1.5	35	41
4	Ridg5	5	3.5	96	92	31.1	85	1.75		53.5
"	Ridg6	6	16.5	92	91.5	23.6	88	120		63.5
"	Ridg7	7	23.5	89	71	37	76	1.75		32
5	Ridg8	8	3.5	239	225	32.6	76	2		46
"	Ridg9	9	16.5	211	216	29.7	81	1.75		29.2
"	Ridg10	10	23.5	199	204	---	83.5	1.75	10	29
4.5	Ridg11	11	3.5	103	90	23.5	88.3	---		50
"	Ridg12	12	3.5	103	90	28.3	88.3	1.75		32.5
"	Ridg13	13	16.5	83	79	---	82	1.75		20
"	Ridg14	14	23.5	74	80	28.5	88	1.92	20	24.8

Notes:

1- Time interval between two successive tests, 2- Observed basic infiltration rate (drained water), 3- Calculated from water balance equation

Table 4.2 Water application rate measurements (contd.)

Nozzle size (mm)	Simple plane test	Test no.	Soil slope (%)	Pressure (bar)	Application rate (mm/hr)		Soil water content (%) (by volume)	Coefficient of uniformity (%)	Time interval (hr) ¹	Basic infiltration rate (mm/hr)	
					1- can	2- tray				Observed ²	Calculated ³
3	Plane 1	12	4.7	1.5	65	50	3.7	89	---	---	47.5
"	Plane 2	13	4.7	1.5	65	50	29.6	89	20	---	47.5
"	Plane 3	14	4.7	1.5	65	54	31	89	1.16	---	41.5
"	Plane 4	15	16.5	1.5	57	50.5	33.6	93	63	---	42
"	Plane 5	16	16.5	1.5	57	50.5	30.4	93	1.75	---	31.6
"	Plane 6	17	16.5	1.5	57	50.5	33.8	93	42	36	36
"	Plane 7	18	23.5	1.5	54	45	31.4	84	3	20.5	30.5
"	Plane 8	19	23.5	1.5	54	45	---	84	1.75	18	17
"	Plane 9	20	23.5	1.5	54	45	31.3	84	17.25	---	30.5
"	Plane 10	1	4.7	1.2	44	---	37.2	90	58	---	---
"	Plane 11	2	4.7	0.83	20	---	36.7	80	16.5	---	---
"	Plane 12	3	4.7	2	65	---	36.1	87.6	2	19	19
4	Plane 14	5	4.7	1.33	154	151	28.8	87.6	18	---	19.4
"	Plane 15	6	10	---	147	138	32.9	91.6	2	---	7
"	Plane 16	7	23.3	1.33	132	108	34.6	82.5	64	---	---
5	Plane 17	8	4.7	1	212	212	36	88.5	---	---	37
"	Plane 18	9	10	2	311	277	33.9	87.5	16	---	14
"	Plane 19	10	23.5	1	195	204	34.5	81	---	---	27
"	Plane 0	11	0	1	227	189	34.5	82	---	8.5	6
4.5	Plane 13	4	4.7	2.67	112	---	---	82.3	---	---	28

Notes: 1- Time interval between two successive tests, 2- Observed basic infiltration rate (drained water), 3- Calculated from water balance equation

4.3.1.1 Water distribution uniformity

The coefficient of distribution uniformity (CDU) indicates how well the applied water is distributed on the catchment area. Water distribution uniformity was measured using a grid of catch-cans laid out on a 500 mm grid on the tray. Then the uniformity coefficient was determined using Christiansen method (see section 2.6.4). The ideal distribution of water is achieved when CDU is equal to unity. Proper selection of nozzle pressure, nozzle size, spacing and suitable height will improve this coefficient (Murugaboopath 1987). So a coefficient that is more than 75% can be acceptable for rainfall runoff tests (personal communication with Morgan 1995).

4.3.2 Effect of water pressure

System pressure is one of the dominant factors that affects the water application rate of a rainfall simulator. Since the flow rate follows the power relationship with respect to pressure, the application rate also follows the same type of relationship (Murugaboopath 1987).

$$i = mp^n$$

4.1

where i is the intensity of water application (mm/hr), p is pressure in K_{pa} , m and n are the coefficients.

However, there is an interaction between pressure and the number of nozzles. The number of nozzles were selected so that the maximum uniformity coefficient was achieved. In this study, one nozzle was setup at the height of 2.2m above the soil tray, then the uniformity distribution of water was examined for different pressures. The results showed that the uniformity coefficient for single nozzle was often less than 73%. So the single nozzle was

rejected for this experiment. In the second trial three nozzles were spaced 650 mm from each other so there was enough overlap to cover the whole tray. As indicated in Table 4.3 the highest uniformity obtained for three nozzles when the pressure lay between 1.1 to 3 bars.

As indicated in Table 4.3, Figures 4.2 and Figure 4.3 when the pressure of nozzle increases the water application rate also increases. However, the rate of change in water application rate at high pressure is lower than that at low pressure. Low pressure also affects water distribution uniformity. To investigate this a series of uniformity tests were conducted for different nozzles at different pressures. Table 4.4 shows the spray nozzle operating characteristics (coefficient of distribution uniformity and water application rate for different nozzles at different pressures). From this table and Figures 4.3 can be seen

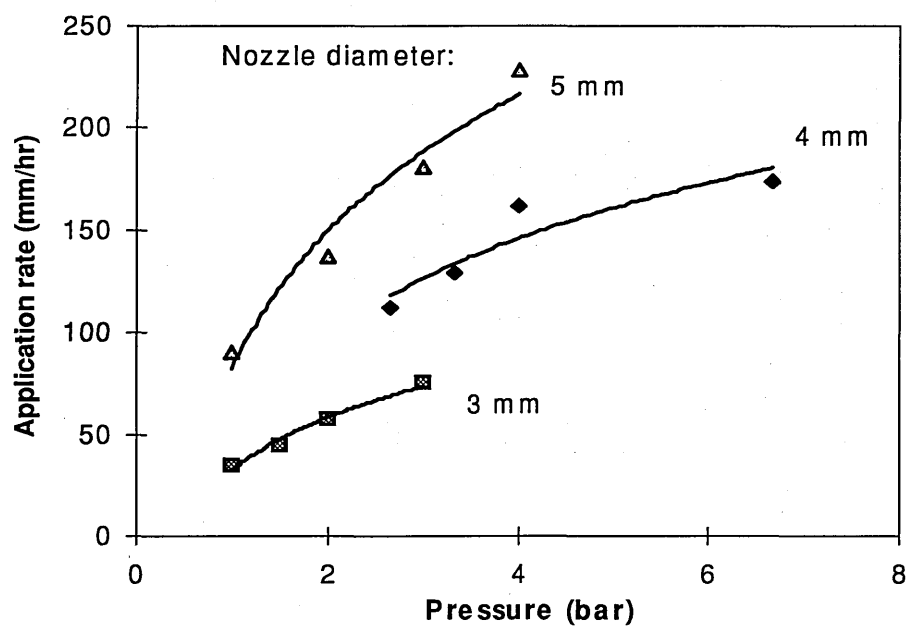


Figure 4.2 Changes in water application rate with pressure and nozzle diameter (three nozzles)

Table 4.3 Uniformity coefficient for single and triple nozzles (size = 3 mm)

No-nozzle	Height (m)	Pressure (bar)	Uniformity Coefficient (%)	Application rate (mm/h)	Area (m ²)	Slope (%)
Single	2.2	2	61	222	2.5	4.7
	2.2	6	73	57.4	2.5	4.7
	1.7	1.5	65	125	2.5	4.7
	1.7	2	70	116.4	2.5	4.7
	1.7	3.9	73	94	2.5	4.7
Triple	1.7	4.7	77	82	2.5	4.7
	1.7	5	78	152	2.5	4.7
	2.2	1.1	79	42.3	2.5	4.7
	2.2	2	80	60	2.5	4.7
	2.2	2.2	85	66	2.5	4.7
	2.2	3	87	72	2.5	4.7
	2.2	3.33	79	77.4	2.5	4.7
	2.2	4.4	74	97	2.5	4.7
	2.2	1	79	34.5	2	0
	2.2	1.5	86	44.6	2	0
	2.2	2	82	57.3	2	0
	2.2	3	82	75	2	0

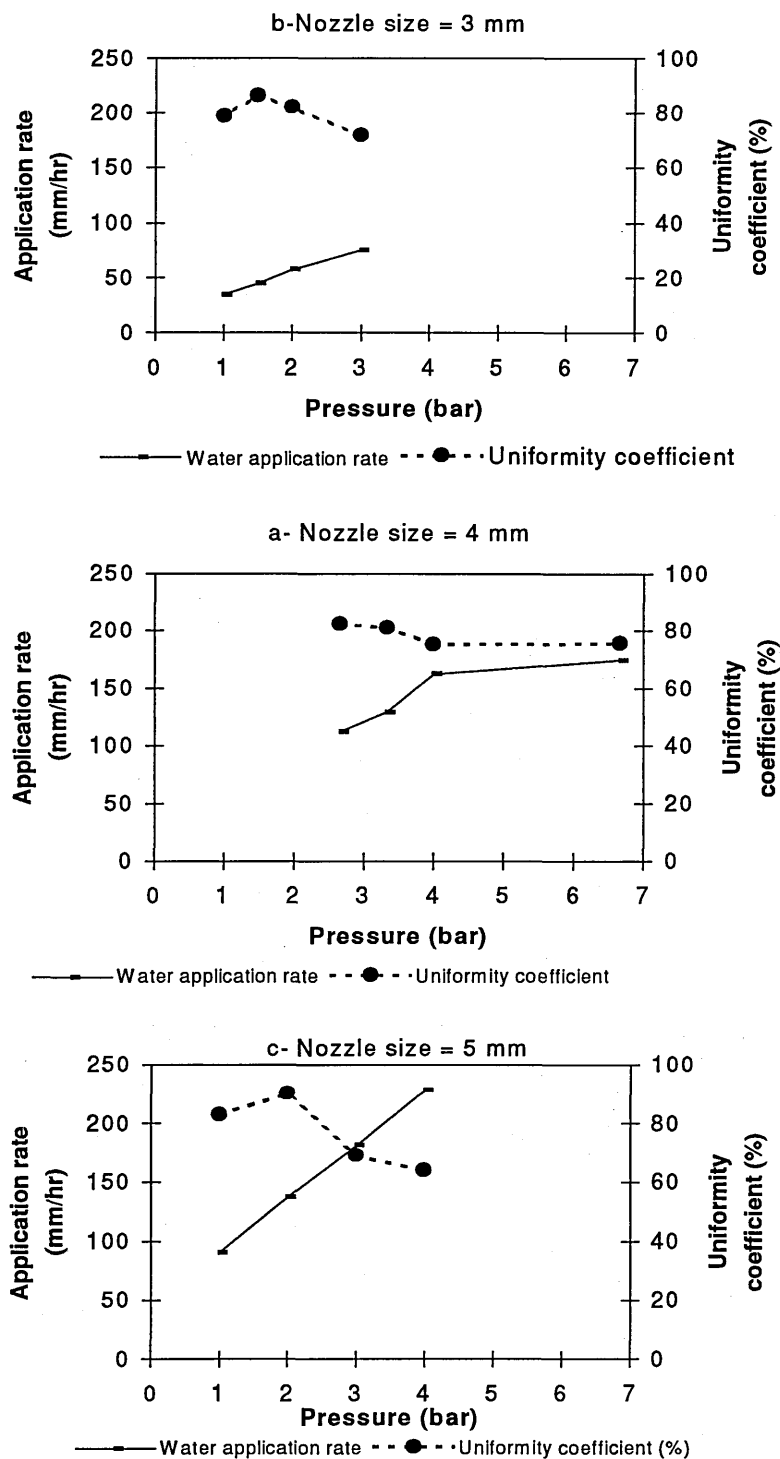


Figure 4.3 Changes in water application rate and uniformity coefficient with pressure.

Table 4.4 Spray nozzle operating characteristics (three nozzles)

Nozzle size (mm)	Pressure (bar)	Coefficient of uniformity (%)	Application rate (mm/hr)
3	1	79	34.5
	1.5	86.4	44.6
	2	82	57.3
	3	72	75
4	2.67	82.3	112
	3.33	81	129
	4	75.2	162
	6.67	75.5	174
5	1	83	90.5
	2	90	137
	3	69	181
	4	64	228

observed that when the pressure increases the coefficient of distribution uniformity increases until $p=1.5$ bar and then it begins to decline slowly. The results show that the coefficient of distribution uniformity is low at either high or low pressure. It is maximum at $p = 1.5$ bar on a zero slope surface. This pressure value was selected to run the experiments in this study in order to achieve the highest coefficient of distribution uniformity. Thus a line with three nozzles spaced at 650 mm was selected to operate at 1.5 bar for the main experiments. The recommended height of the nozzles was 2.2 m. Area of tray was also changed from 2.5 to 2 m² to bring the tray with the area of uniform application.

4.3.3 Water application rate and slope

The water application rate changes when the slope inclines from horizontal level condition. According to Figure 4.4, theoretically the mean water application rate reduces with increasing the slope. This is because the projected area at steeper slope (S_1) is less than the area for slope S_0 , i.e.

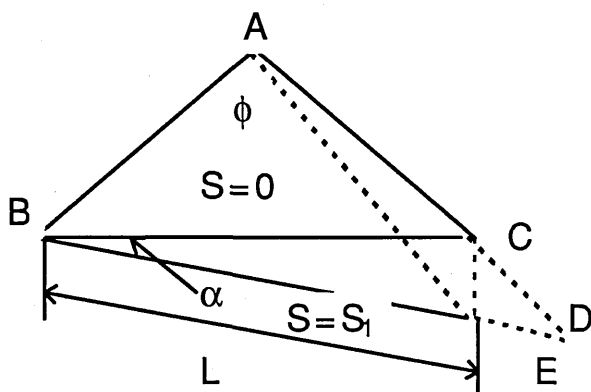


Figure 4.4 The effect of slope on water application rates

$$BD = \frac{L}{\sin(\pi/2 - \alpha - \phi/2)} \times \sin(\pi/2 + \phi/2) \quad 4.2$$

In which BD = the new length of micro-catchment at S_I , L = the length of micro-catchment at S_o , α = the angle between the horizontal line and the longitudinal slope of catchment (degree), ϕ = the angle between the out most spray lines that touch the up and bottom of micro-catchment at zero slope. The observed data in the laboratory confirms this phenomenon.

As illustrated in Figure 4.5, as the slope of the soil tray increases, the projected area and consequently water application rate reduce. This reduction is more for high and medium water application rates than for low water application rates (less than 60 mm/hr). So to achieve the real water

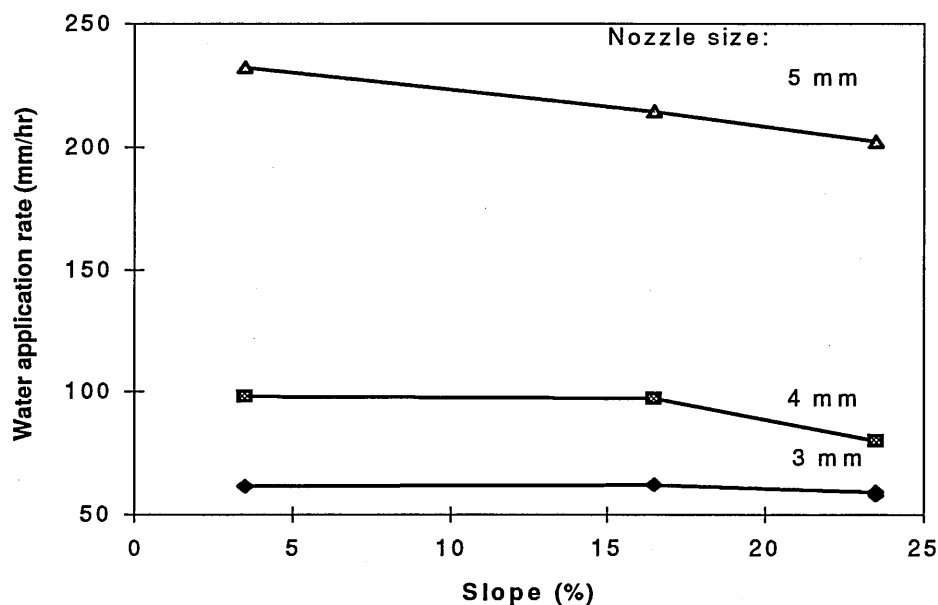


Figure 4.5 Effect of slope on average water application rate

application rate on slopes other than zero, a correction must be applied to zero slope catchment length using equation 4.2.

4.3.4 Application rate and methods of measurement

In this section two methods of measuring the average of water application rate, whole impervious catchment (tray) and catch-can methods, are compared. In Figure 4.6 water application rate is plotted against pressure for two nozzle sizes (4 and 5 mm) and two methods of measurement. As can be seen water application rate increases as the pressure increases. At low pressure water application rates are more or less equal, but at high pressure the catch-can method often underestimates the application rate compared to whole the catchment (tray) method. Thus for the low pressures any of these measurements can be recommended but for high pressures the whole catchment method is recommended for the model validation. This is because the bigger the area, the more accurate the value of measurement.

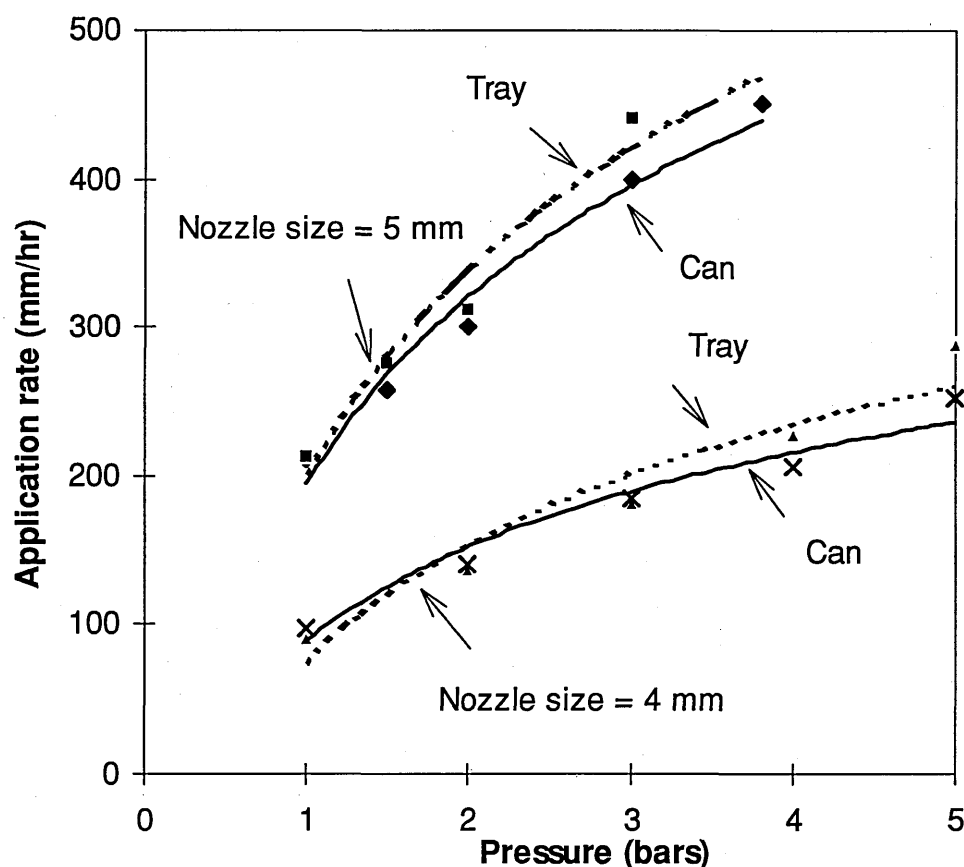


Figure 4.6 Comparison between two methods of measuring water application rate (can and tray)

4.4 Soil mechanical analysis

Soil mechanical analysis is necessary to find the soil texture and soil particles distribution. To do this, three samples were taken from depths 0 to 100 mm in the field before doing tests and three samples after running the tests from the tray soil and analyzed in the laboratory. Pipette method was used to find the amounts of sand, silt and clay in the samples. The USDA standard was used to determine the size of the soil particles. The soil texture was found, from the data and the soil textural triangle, to be a sandy loam. The results of soil

Table 4.5 Soil mechanical analysis using pipette method.

Sample*	Sand %	Silt %	Clay %	Texture
Before soil tray tests:				
1	71.9	15.1	12.9	Sandy loam
2	69.4	17.5	13.2	Sandy loam
3	75.6	13.4	10.9	Sandy loam
Total	216.9	46.0	37.1	
Mean	72.3	15.3	12.4	Sandy loam
After soil tray tests:				
4	72.8	14.4	12.8	Sandy loam
5	70.1	16.6	13.3	Sandy loam
6	73.3	12.7	13.9	Sandy loam
Total	216.3	43.7	40.0	
Mean	72.1	14.6	13.3	Sandy loam

Rock fragment = 5 %

Note: The soil samples were analyzed before and after running the laboratory tests (soil tray test).

mechanical analysis are presented in Table 4.5. The soil particle distribution curves are shown in Figure.4.7.

4.5 Saturated hydraulic conductivity

The saturated hydraulic conductivity of a sandy loam soil was measured in the field under sprinkler irrigation and in the laboratory free from rainfall conditions using different methods. These methods are falling head, water balance equation and drained water collected from the soil tray. The falling head method was used in the laboratory to measure the hydraulic conductivity free from rainfall for both disturbed and undisturbed soil samples

Figure 4.8 shows the typical example of basic infiltration rate (or saturated hydraulic conductivity) resulting from the infiltration tests for the field and laboratory experiments. These values have been calculated using water

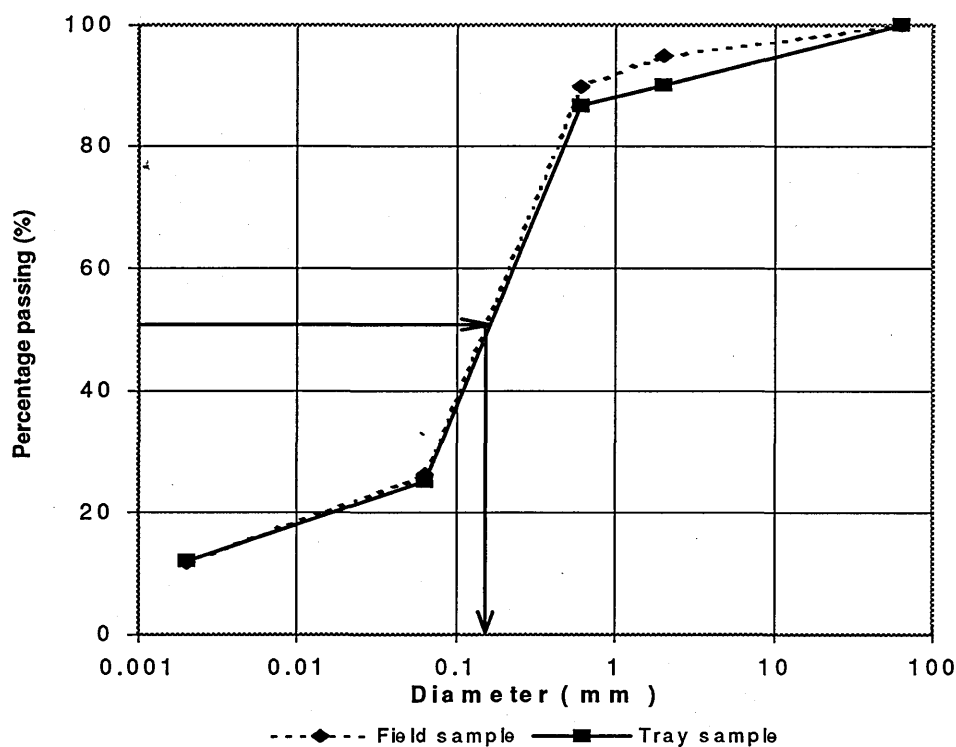


Figure 4.7 Particle size distribution

balance equation. In this study the basic infiltration rate was measured at an equilibrium condition, assuming that the soil was fully saturated and changes in soil water content were zero.

Table 4.6 shows the hydraulic conductivity values calculated from water balance equation for the laboratory experiments. These are compared with the data which was observed by collecting the drained water in the laboratory (direct method). The statistical analysis shows there is no significant difference between calculated values from water balance and observed data. The regression coefficient is also high ($R^2 = 0.962$) indicating a high goodness-of-fit between them. Table 4.7 shows a summary of saturated hydraulic conductivity values for a sandy loam soil calculated from different approaches in the field and laboratory. These values which range from 3 to 52 mm/hr are

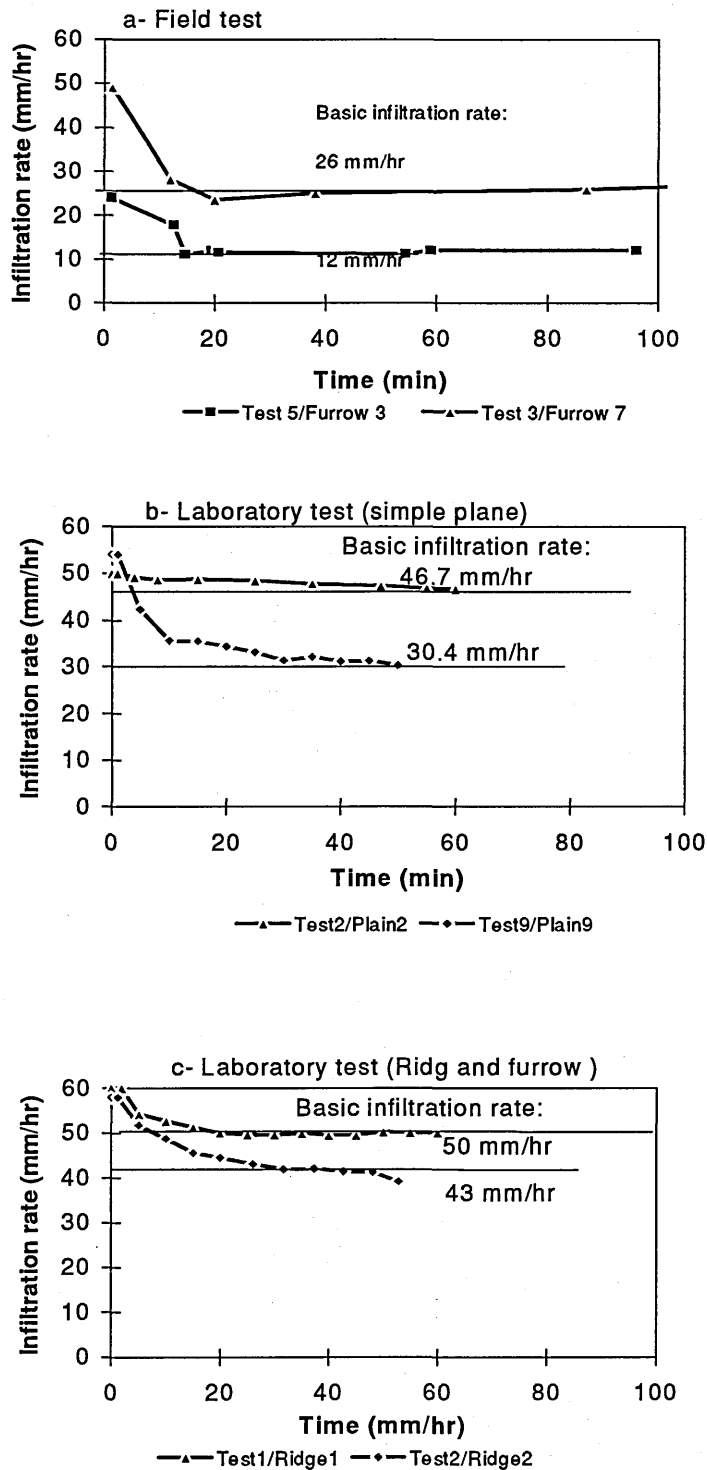


Figure 4.8 Typical example of basic infiltration rate ($\approx$ saturated hydraulic conductivity)

Table 4.6 Comparison between calculated and observed saturated hydraulic conductivity

Type	Plane6	Plane7	Plane8	Plane20	Ridg4	Ridg10	Ridg14
Calculated (water balance)	36	30.5	17	6	41	29	20
Observed (drained water)	36	20.5	18	8.5	35	10	24.8
T-test= -2.8 < 2.57 non-significant							
R ² = .962							

Table 4.7 A summary of hydraulic conductivity for the laboratory and field experiments

Method	Condition	Test	Hydraulic conductivity (mm/hr)
Falling head:	undisturbed soil	Column	3-10
	disturbed soil	Column	28-52
water balance:		Field site	13-27
		Soil tray	6-52
Observed:		Soil tray	8.5-36

Note1: (7),(26),(190) mm/hr are low, mean and high values of saturated hydraulic conductivity for a sandy loam soil reported in the KINEROS user guide (Woolhiser et al, 1990).

in the limit reported in the literature for a sandy loam soil (e.g. EUROSEM User Guide, 1992). A more detail of saturated hydraulic conductivity measurements in the field and laboratory is presented in Appendix B.1.

Depending on the soil conditions (disturbed or non-disturbed, compacted or non-compacted), longitudinal slope, under rainfall or free from rainfall and irrigation event number, the saturated hydraulic conductivity values change. So the saturated hydraulic conductivity of a soil, under water application, changes locally and temporarily. For example, as demonstrated in the Figure

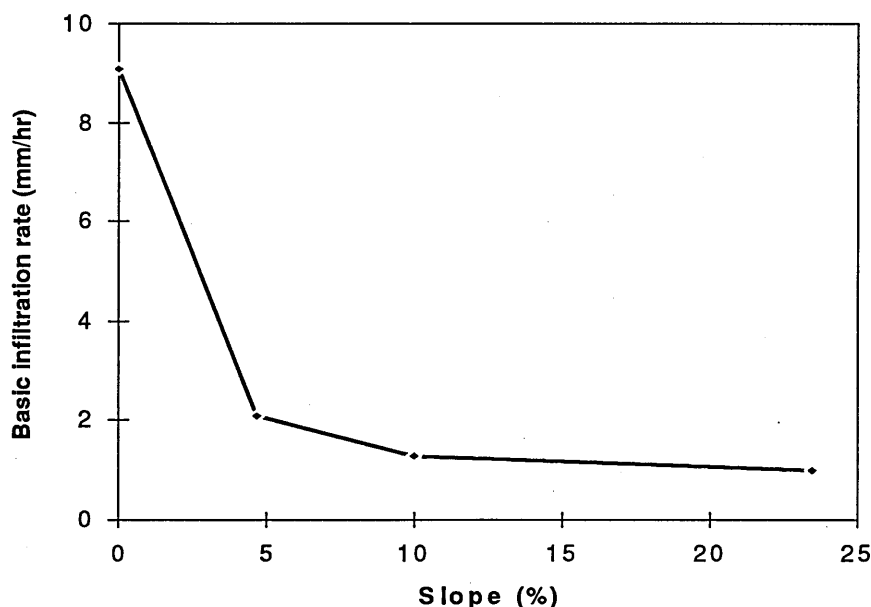


Figure 4.9 Effect of slope on basic infiltration rate

4.9, when the slope of the catchment increases the final infiltration rate (saturated hydraulic conductivity) reduces. The value of saturated hydraulic conductivity for the slope 0.0 is the largest, and then starts to reduce non-linearly with slope. This is because when the slope is low the opportunity for water to move into the soil is greater. However, under steep slope conditions water moves down the slope and generates runoff rather than infiltration into the soil (ISO 7562, 1995).

The next point is the reduction of hydraulic conductivity with increasing the number of irrigation events, even at the steeper slopes (Figure 4.10). The reasons are the compaction of soil surface by the rain drops, crusting on the soil surface and reducing flux area due to the blocking the soil pores by soil particles (see section 2.5.5). According to Mwendera and Feyen (1993) the final infiltration rate is highly dependent on initial tillage-induced surface roughness and reduces with increasing the accumulated rainfall.

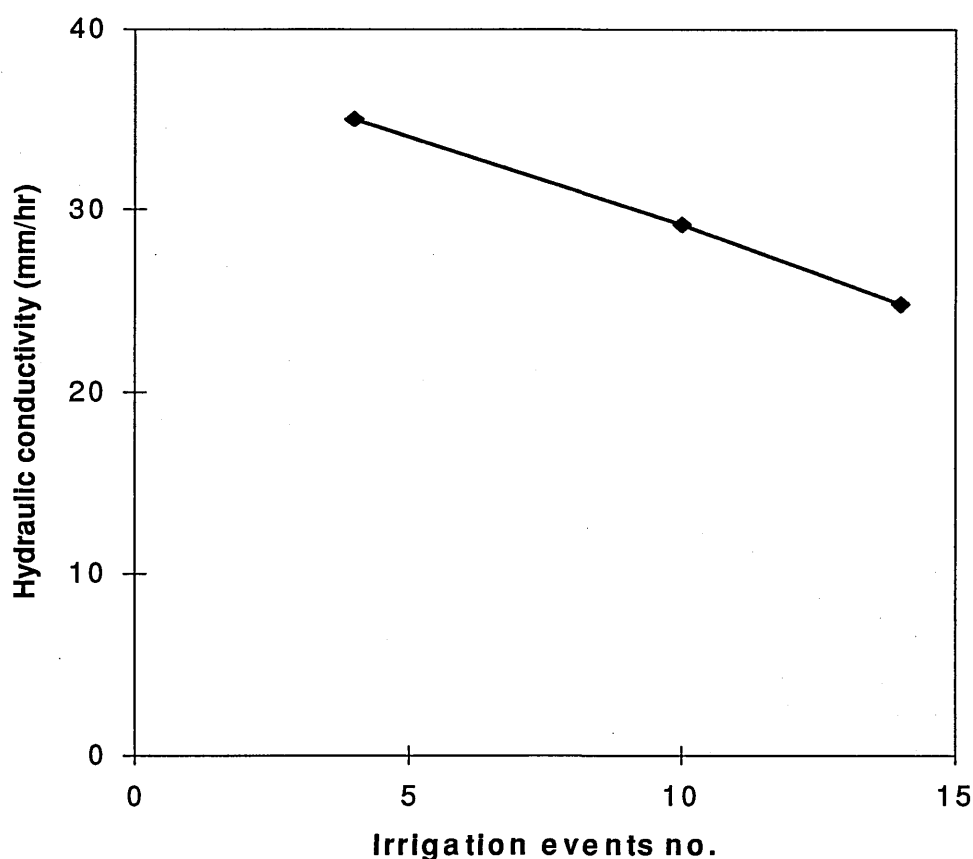


Figure 4.10 Variation of saturated hydraulic conductivity with irrigation events no. for slope = 23.5 %

So due to local and temporal changes in the saturated hydraulic conductivity of a soil, a constant value cannot be recommended for a type of soil, thus the value for each test should be obtained independently. The needed accuracy of hydraulic conductivity values as inputs to the model depends on the objectives and sensitivity of model. For example, if the objectives are to find the time to peak or time to start runoff using the values obtained from falling head method is adequate, because these parameters are not sensitive to hydraulic conductivity. However, if the volume of runoff is the objective the more accurate value such as values obtained from direct measurement or water balance methods are needed, because this output is moderately sensitive to hydraulic conductivity.

The adjusted values which were used to calibrate the model for values of saturated hydraulic conductivity confirm these values. Adjusted values are those values have been used to calibrate the models. So the direct measured values or water balance values can be used as input values for the model validation.

4.6 Capillary drive

Capillary drive is another factor that affects runoff hydrograph. This factor can be calculated using Smith's relationship (1983) or time to ponding approach. Capillary drive depends on the sorptivity of soil that can be significant at early stage of infiltration (personal communication with Young 1997). Sorptivity is a coefficient in Philip's equation which can be found as follows:

$$s_s = I / t^{1/2} \quad 4.3$$

Where s_s = the slope of line or sorptivity, t = time and I = accumulated infiltration. So the sorptivity value was estimated by plotting the infiltration data against the square roots of time ($t^{1/2}$) (Figure 4.11). Then the derived equations in this section were used to find capillary drive value.

Capillary drive was also determined using the time to ponding method. In this method two times of ponding should be recorded for two different water application rates. Then the equations in section (2.5.3) were used to determine the capillary drive value (Figure 4.12).

The capillary drive values calculated from Smith's equation are compared to values found from ponding time method and values reported in the literature (Appendix B.2). The average of capillary drive values estimated from the Smith's equation is between 4 and 59 mm, from ponding time method is 0.6 to

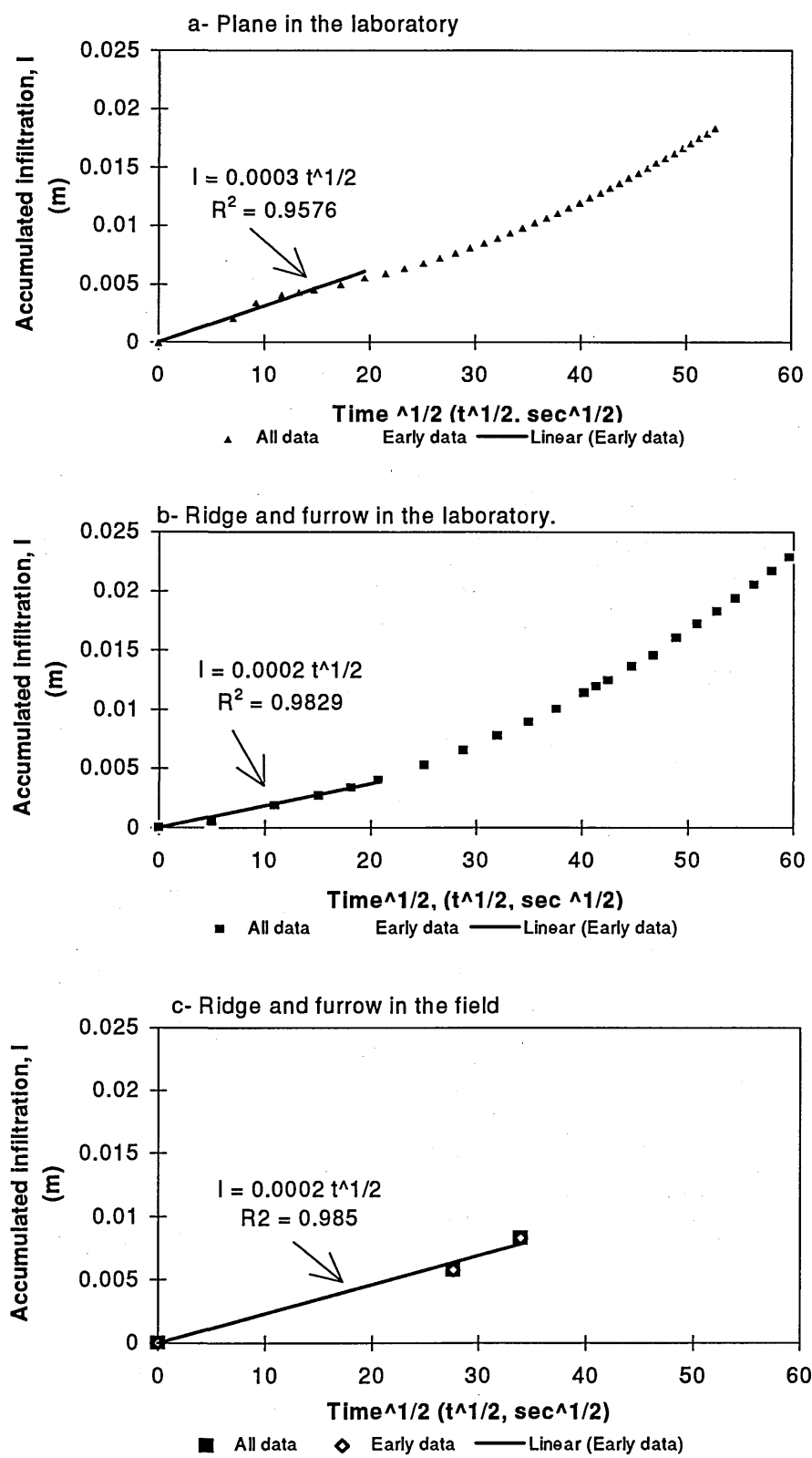


Figure 4.11 Typical examples of the determination of sorptivity (Philip’s equation)

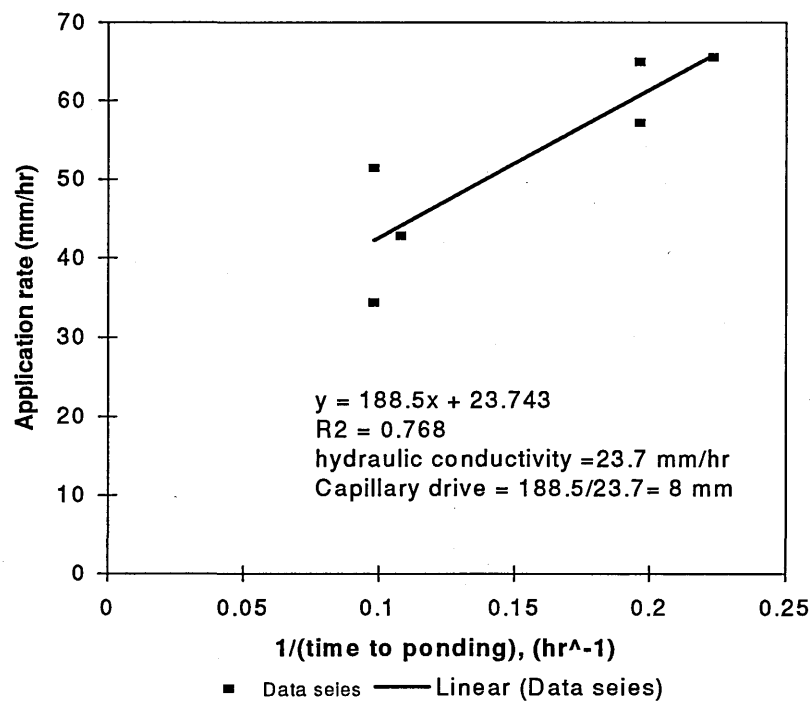
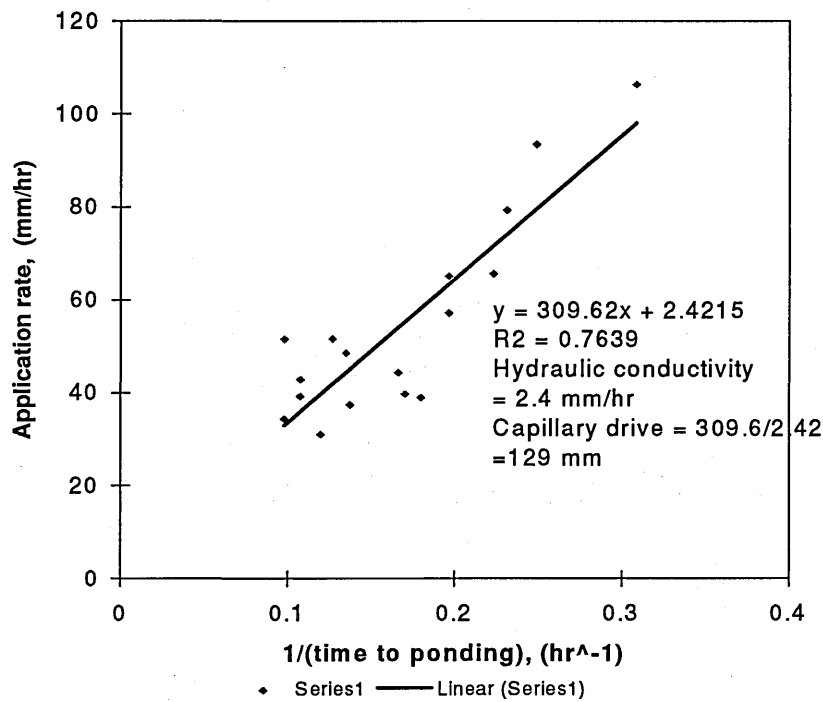


Figure 4.12 A plot of water application rate against inverse of time to ponding ($1/t_p$)

128 mm and in the literature is 98 to 526 mm. Although the capillary drive value can be calculated using Smith's equation and time to ponding method, this parameter should be calibrated for validation purpose. This will be discussed in the next chapter.

4.7 Determination of Manning's coefficients

Manning roughness coefficient affects runoff flow, especially short time events (see section 2.4). So it is necessary to estimate this coefficient and use it as an input in the model. This was measured using two techniques, depth-flow stage and Strickler methods. To carry out the first approach the depths and rate of overland flow were measured with respect to time during the field experiments. Then the Manning formula was applied to calculate the 'n' value. The average of values from this method was 0.028 and is in the range of a bare soil reported by other researchers (Table 4.8).

Table 4.8 Manning's n computed from depth-flow stage

Time (min)	Flow rate (m ³ /hr)	Depth (m)	Manning's n m ^{1/6}
0	0	0	
24	0.288	0.0026	0.022
44	0.432	0.0038	0.028
76	0.576	0.0048	0.031
92	0.596	0.0048	0.030
Mean n			0.028

The Strickler method was also used to calculate Manning's n for a variety of soil particle diameters such as 20, 25, 40, 50, 75 and 90 percent of particles passing. The following formula was used for this purpose:

$$n = .041d_x^{1/6}$$

4.4

Where d_x = Diameter of percentage of particles passing (m) and n = Manning's coefficient ($m^{1/6}$). The calculated values are presented in Table 4.9. According to this table the calculated Manning coefficients are in the range reported in the literature (e.g. KINEROS user guide, 1990), while the diameter of more than 50 percentage particles passing is applied. These values should be corrected, if the percentage of rock fragment is more than 10 % (see section 2.4.1). The percentage of rock fragment was less than 5 % in this research. In this case the Manning coefficient is still 0.01 or more (Table 4.9).

Table 4.9 Manning's n calculated using Strickler equation

Percentage (x)	20	25	50	60	75	90
less than						
Diameter (mm)	0.015	0.06	0.15	0.21	0.37	1
n ($m^{1/6}$)	0.006	0.008	0.01	0.01	0.011	0.013

These values are related to soil particle size and excluding micro-topographic feature of soil surface. Considering the micro-topographic feature (form roughness), a value of 0.03 for 'n' which is close to the value predicted by depth-flow stage method seems to be reasonable for this study..

4.8 Observed runoff hydrographs

In the laboratory some of parameters were examined to see their effects on runoff process. In this section some of these factors such as soil water content, longitudinal slope and water application rate are discussed briefly.

4.8.1 Effect of initial soil water content

As discussed in section (2.6) the infiltration capacity depends on the initial soil water content and the rainfall already absorbed into the soil (Woolhiser et al, 1990). A micro-catchment with low soil water content generates less runoff than a micro-catchment with high soil water content under the same conditions (Figure 4.13-a). The water content of soil declines as the time interval between two successive irrigation becomes larger. As indicated in Figure 4.13-b, the longer the time interval between two irrigation events, the lower the initial water content of the soil and consequently the lower the volume of surface runoff. More runoff is generated when the soil is fully saturated.

4.8.2 Effect of longitudinal slope

On steep slopes, the soil surface detention storage and also the infiltration rate are reduced and runoff flow rate increases (Figure 4.14). Therefore, the slope affects flow velocity, time to start, time to peak and time to stop runoff. So the greater the longitudinal slope the shorter the time to start, time to peak and time to stop runoff (or duration of runoff) and the higher the velocity of flow. Obviously the initial soil water content affects the time to runoff and early stage of runoff hydrograph (see section 5.2.2). However, there is an interaction between the effect of initial soil water content and longitudinal slope on the time of start runoff. More accurate tests are needed to find the effect of this interaction on time to start runoff, time to peak and time to end overland flow.

4.8.3 Effect of water application rate

When the soil surface detention storage is satisfied overland occurs (see section 2.4.2). Overland flow mainly depends on the water application rate so

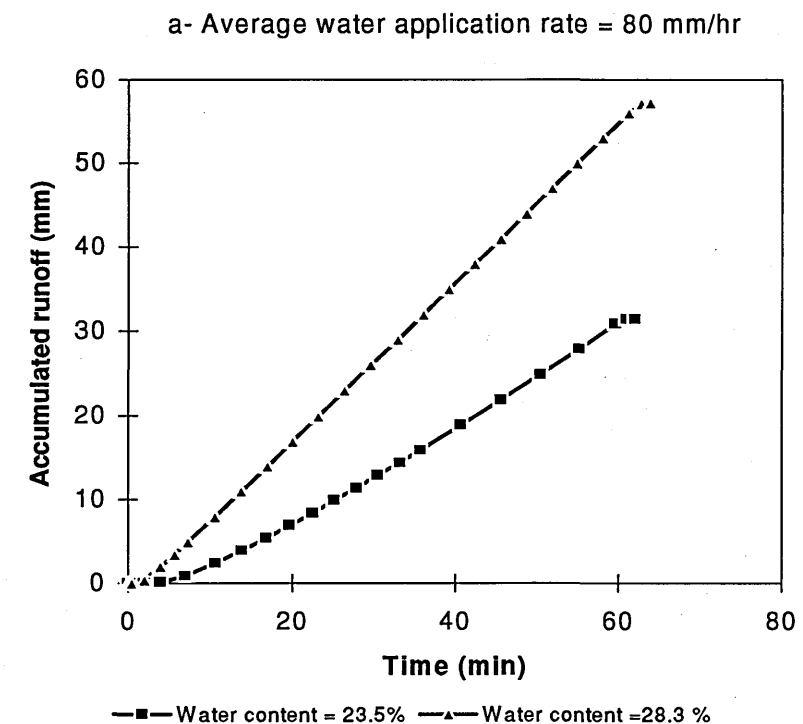
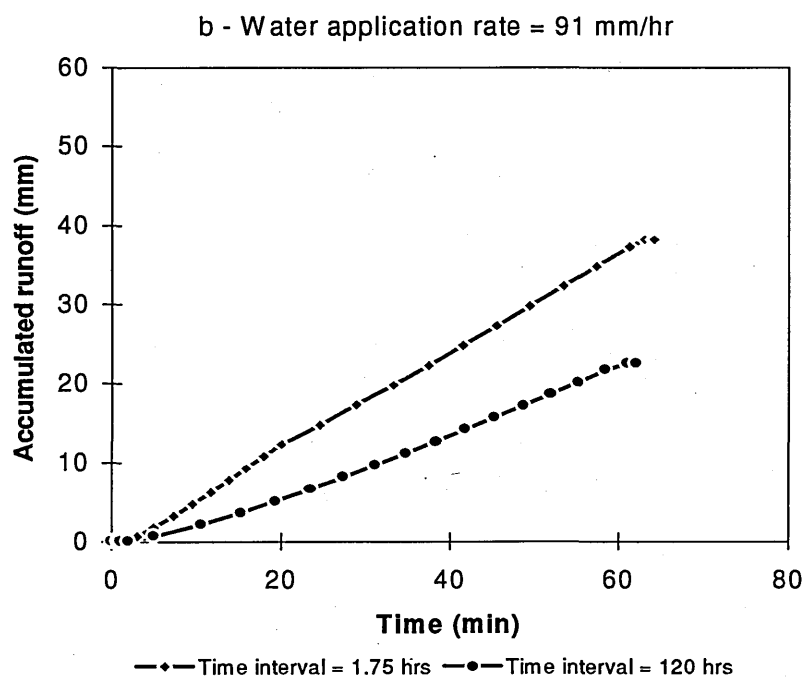


Figure 4.13 Effect of soil water content on runoff hydrographs

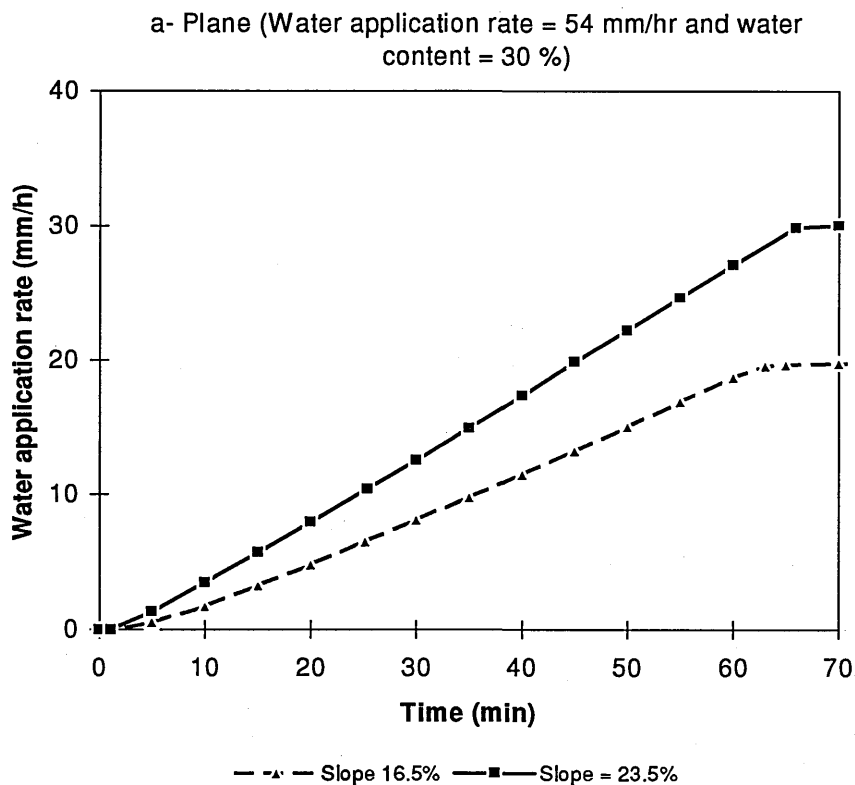
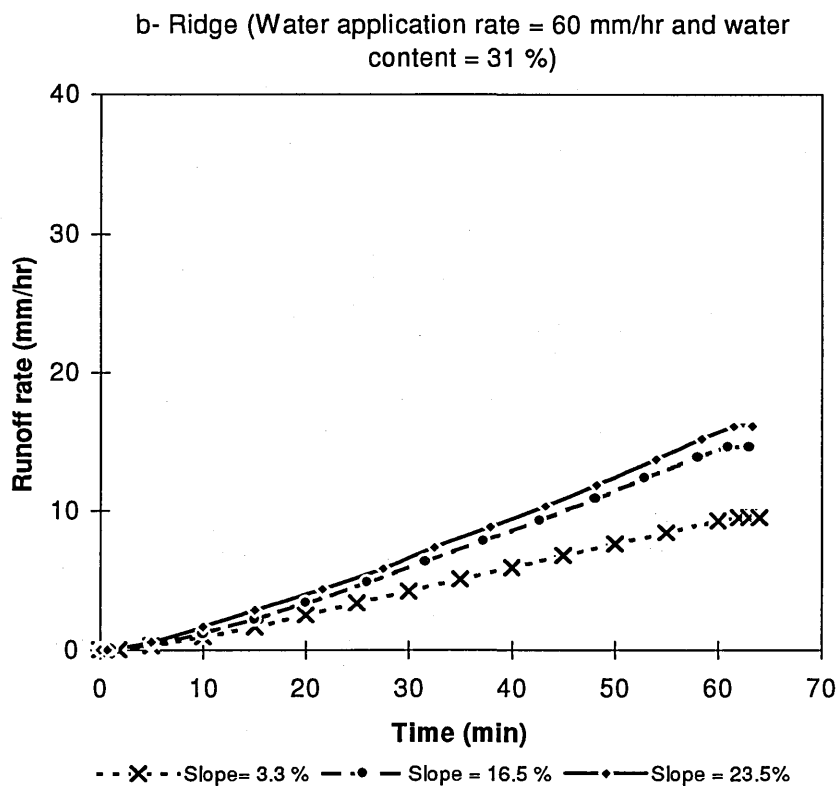


Figure 4.14 Effect of longitudinal slope on runoff hydrograph.

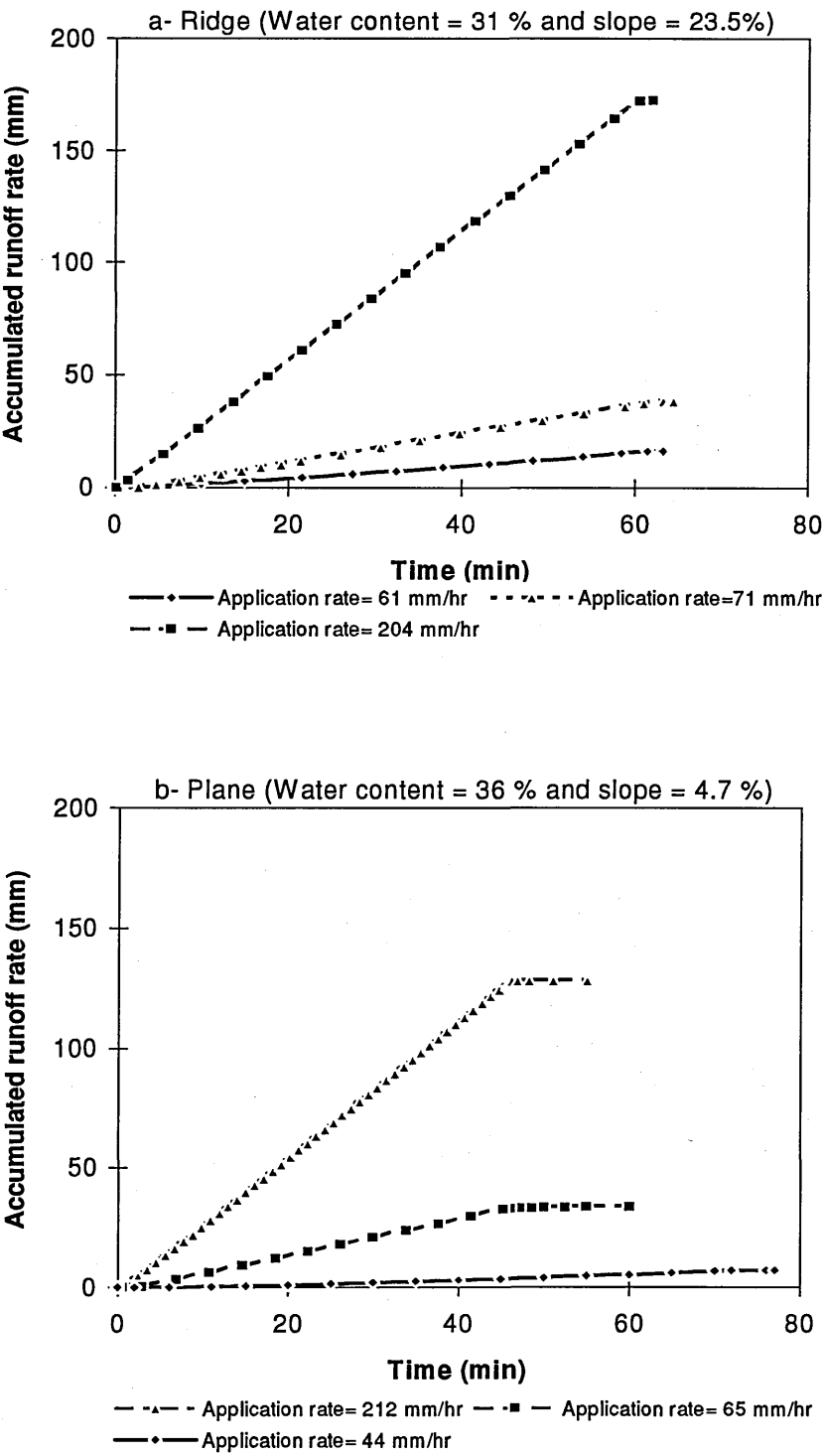


Figure 4.15 Effect of water application rates on runoff hydrographs.

that the greater the water application rate the greater the surface runoff rate (Figure 4.15). High water application rates not only cause more excess rainfall but also damage the soil surface structure and reduce infiltration rate. This in turn leads to high runoff rate and soil erosion. High water application rate effects become more serious when accompanied with greater longitudinal slopes.

4.9 Statistical techniques to describe model analysis

Comparing the time dependent output of physically-based runoff models requires approaches that depend on the modeling objectives. The objectives of single event modeling such as EUROSEM or KINEROS are the determination of peak flow rate, runoff volume and hydrograph shape. According to Green and Stephenson (1986) no single statistical goodness of fit criterion is sufficient for all purposes to evaluate adequately the fit between observed and predicted hydrograph. The following techniques are described to assess the hydrographs and related parameters in this study.

4.9.1 Sum squares of residual method

The sum squares of residual method can be written as follows:

$$D = \sum [q_p(t) - q_o(t)]^2 \quad 4.5$$

In which $q_p(t)$ = value on predicted hydrograph for time (t) and $q_o(t)$ = value on observed hydrograph for time (t). This formula gives an absolute difference between two curves. This method is mainly used for assessing the overall goodness-of-fit or shape of a simulated hydrograph for a single event. Since it concerns absolute differences it gives more weight to discrepancies between higher values.

4.9.2 Model efficiency

Model efficiency is another tool that gives a relative difference between observed and predicted values. This technique is an index of disagreement between observed and simulated hydrographs. It was favoured by many researchers such as Nash and Sutcliffe (1970) and Quinton (1994a). It provides a dimensionless value which approaches to one when the difference between the predicted and observed values becomes small. A value less than zero indicates that the model predictions would be worse than applying the averaged observed values for estimation. This coefficient compares the measured values to a 1:1 line of observed values equal the predicted values, rather than to a best fit regression line.

The index of disagreement can be expressed by the following relationship (Nash and Sutcliffe, 1970):

$$F^2 = \sum (q_o - q_p)^2 \quad 4.6$$

Where q_o and q_p = the observed and computed discharge at corresponding time, F^2 is analogue to the residual variance of regression analysis. The initial variance F_o^2 can be defined as :

$$F_o^2 = \sum (q_o - \bar{q}_o)^2 \quad 4.7$$

$\bar{q}_o$ = the mean of observed data, F_o^2 can be defined as the "no model " value of F^2 . So the efficiency of model can be defined as follows:

$$R^2 = \frac{F_o^2 - F^2}{F_o^2} \quad 4.8$$

R^2 = model efficiency (analogous to coefficient of determination)

4.9.3 Root mean-squared-error (RMSE) method

The root mean-squared-error (*RMSE*) method was first used by Party and Marino (1983) to examine the sensitivity of a nonlinear rainfall runoff model to variation in some parameters, in both calibration and verification stages. After that other researchers such as Zhao et al.(1995) also used this technique as follows to analysis the unit hydrographs:

$$RMSE = \frac{\sqrt{\sum [q_o(t) - q_p(t)]^2}}{N} \quad 4.9$$

Where N = the number of ordinates for direct runoff hydrograph, $q_o(t)$ and $q_p(t)$ = observed and predicted runoff rates.

4.9.4 Regression analysis

The association between observed and predicted data can be assessed by using the regression analysis. Using this technique, the square of the slope of best fit line or coefficient of determination (R^2) expresses the percentage of variation explained by the regression line. It is also a criterion of parameter stability. The computed regression coefficient (R) can be judged against the tabulated values at a certain level of probability to accept or reject it. The confidence limits are also determined at a certain level of probability for the regression line, the slope of line and intercept as described in statistical references. This method was also recommended to assess the hydrographs and related parameters (personal communication with Marshal, 1996).

The last three methods have been used for the analysis of models in this research. However, as indicated by Green and Stephenson (1986) no

hydrograph comparison would be complete without a plot of predicted and observed hydrographs.

4.9.5 Optimisation of parameters and their stability

Automatic optimization was suggested by O' Donnell (1966) to determine the parameter values or to remove subjectivity in fitting the model to the data. In this method the improvement of fitting is tested by successive changes of parameter values and taking into account the results of previous steps.

Optimisation needs an index of agreement or disagreement between observed and computed discharge. This assessment can be carried out by using model efficiency (equation 4.8). The efficiency of model parts (r^2) can be judged by the insertion of a parameter and calculating F^2 before and F^2 and r^2 after the insertion of model parameter.

$$r^2 = \frac{F^1 - F^2}{F^1} \quad 4.10$$

In which suffixes 1 and 2 refer to before and after insertion of the model part. A significance test for correlation coefficient (R^2 and r^2) would be useful by using the standard test. By the way, R^2 and r^2 are useful indices for a general interpretation of the efficacy of a model or part (Nash and Sutcliffe, 1970). F^2 is a function of input and output and parameter space. Optimization involves finding the values of parameters which minimise F^2 . The "steepest descent" method can be used for this purpose (Nash and Sutcliffe, 1970).

If the F^2 curve with respect to a parameter (Figure 4.16) contains only one minimum, it is easy to find it by the steepest descent method, where several minima exist the whole range of parameters should be searched. The stability

of optimum value of parameter can be determined by using the shape of F^2 curve in the vicinity of the optimum point (Nash and Sutcliffe, 1970). The greater the radius of curvature at optimum value of parameter, the less well the parameter value can be defined and the less well will be stability. The higher the angle of intersection of (d^2F^2/dx^2) , the better is the definition of

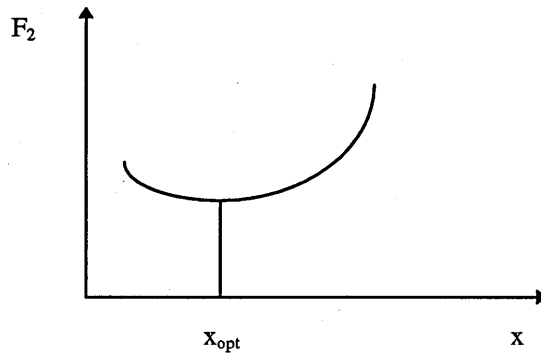


Figure 4.16 Function of sum of squares of residual and the optimum value of parameters

x_{opt} . Thus the value of the second derivative at x_{opt} is an index of the stability of x_{opt} .

4.10 Conclusions

Real data are necessary for the evaluation of a mathematical model. Data can be collected in the field or laboratory. In order to collect a series of accurate data for validation purpose preliminary tests were carried out to set up the rainfall simulator properly. The preliminary experiments in the laboratory showed that a rainfall simulator with three fixed spray nozzles at the height of 2200mm was necessary to apply water uniformly. To attain an adequate water distribution uniformity (more than 80 %) over the soil tray, the system pressure should be around 1.5 bars.

The actual average water application rate on steep slopes was less than the zero slope. Therefore, a correction is necessary for the steep slopes with reference to calibrated graphs. The observed data indicated that the runoff hydrographs are sensitive to water application rate, longitudinal slope, initial soil water content, capillary drive and hydraulic conductivity. Therefore, the proper values of these parameters are necessary for model validation.

The hydraulic conductivity values of a soil under rainfall (or sprinkler irrigation) and free of rainfall are different and change locally and temporarily. Therefore, a constant value cannot be recommended for a type of soil, thus the value of each test should be obtained independently. The needed accuracy for values of hydraulic conductivity as input in the model depends on the objectives and sensitivity of model. This means some of hydrograph parameters such as runoff volume are sensitive and some parameters such as time to runoff and time to peak are insensitive to hydraulic conductivity. Therefore, the more accurate values of hydraulic conductivity are required for the validation of first group than that for the second group of parameters.

Although the capillary drive values estimated from infiltration and time to ponding tests are different from those in the literature, these values are close to the calibrated values which will be discussed in the next chapter.

CHAPTER 5

MODEL VALIDATION FOR STATIONARY SPRINKLERS IN THE LABORATORY

5. Model validation for stationary sprinklers in the laboratory

5.1 Introduction

This section describes laboratory experiments undertaken to validate the model developed in chapter 3 to predict runoff from micro-catchments for stationary sprinkler conditions. The experiments involved both ridge and furrow and simple plane sloping surfaces for the laboratory experiments. Before doing any validation practice, the sensitivity analysis is necessary to understand how the model responds to different parameters.

Model testing and calibration

5.2 Sensitivity analysis

The sensitivity analysis helps to assess the rationality of a model, the effect of input errors, identify research needs and the parameters which most influence on outputs. According to Quinton (1994) the sensitivity analysis of KINEROS-EUROSEM model will have two primary objectives. Firstly, to provide information against which the model can be corroborated. Secondly, to understand the model behavior with respect to operating equations. The methodology is based on the selection of model outputs. For the KINEROS-EUROSEM model the output parameters are divided into static and dynamic output files. In the analysis of this model five static outputs and one dynamic outputs are considered. The static outputs which are necessary in this study are the time to start runoff, time to peak runoff, duration of runoff, peak flow rate (mm/hr) and volume of runoff. The dynamic output is the output that takes the form of time series, such as runoff hydrographs.

Quinton (1994) identified two groups of parameters that have the greatest influence over the model outputs such as runoff, soil loss, peak discharge,

peak sediment discharge, time to runoff, time to peak flow and time to peak sediment discharge. The first group are those which influence infiltration rate and second group are those which influence the maximum equilibrium sediment concentration of the flow. He also classified the sensitivity of the model outputs to each of the parameters into four categories: high sensitivity, moderate sensitivity, low sensitivity and insensitivity. Highly sensitive response are those that their sensitivity is greater than 1. For example, the maximum soil water content of soil (THMAX), saturated hydraulic conductivity (FMIN), effective capillary drive (G) and soil water content (THI) can be put in this category. The moderate sensitivity is where the average linear sensitivity is between 1 and 0.5. Many parameters such as Manning's coefficient (RLMANN and IRMANN) and mean particle size (D_{50}) can be put in this category. Low sensitivity is when the relative change in the output parameter is less than half of the relative change in the input, i.e. the average linear sensitivity is between 0.5 and 0.0. A number of input parameters, for instance, side slope (ZLR), rill depth (RILLD) and rill width (RILLW) are in this category. An insensitive response is one where there is no change in the output for any change in the input, for example: plant height (PLANTH) (see Appendix C.1).

In the following section the effect of typical input parameters such as roughness ratio, initial soil water content, hydraulic conductivity and capillary drive on outputs parameters are discussed. This is because the runoff hydrograph and output parameters are sensitive to these input parameters.

The following statistical technique was used to compare the sensitivity of outputs to inputs (Mecuen 1973):

$$sen. = \frac{[(O_2 - O_1) / O_{av.}]}{[(I_2 - I_1) / I_{av.}]} \quad 5.1$$

Where O_2 and O_1 = the output parameters values, I_1 , and I_2 = the related input parameter values, $O_{av.}$ = averaged outputs, $I_{av.}$ = averaged inputs and $sen.$ = the sensitivity value. The sensitivity value is dimension-less, because the nominator and denominator are normalized.

5.2.1 Effect of Manning's roughness on hydrograph and parameters

The sensitivity of KINEROS-EUROSEM model to Manning's coefficient, depending on the objectives, is in the range of sensitive to insensitive. For example the volume of runoff and the peak discharge are low sensitive, time to peak, time to start runoff and time to end are insensitive to Manning's n (see section 2.4). This parameter has already been discussed in chapter two and four.

5.2.2 Effect of soil water content

In this section the model was tested to see how the changes in the values of initial soil water content affect the runoff hydrograph and hydrograph parameters (Table 5.1 and Table 5.2). The model was run for the soil water values of 11, 21, 31 and 41 percent (mostly observed in the experiments), keeping other parameters constant. Each run was allowed to continue for 63 minutes. This task showed that the effect of initial soil water content on time to runoff is more than time to peak and runoff volume. The peak flow rate is low sensitive and time to end is insensitive to changes in initial soil water content (Figure 5.1).

5.2.3 Effect of hydraulic conductivity

The sensitivity analysis was made to see how the changes to the hydraulic conductivity values affect the output parameters values (Table 5.1 and 5.2). The model was run for the hydraulic conductivity values of 12, 24 and 36 mm/hr, keeping other parameters constant. Each run was allowed to continue for 63 minutes. This task showed that the time to runoff is highly sensitive, runoff volume and peak flow rate are moderate sensitive; time to peak and time to end runoff are insensitive to hydraulic conductivity (Figure 5.2).

Table 5.1 Sensitivity analysis of hydrograph parameters to soil characteristics

Parameter	Runoff volume	Peak flow rate	Time to peak	Time to runoff	Time to end
	(mm)	P _r (mm/hr)	T _p (min)	T _r (min)	T _e (min)
Soil water content (%)	0.02	0.002	0.04	0.13	0
Hydraulic conductivity (mm/hr)	0.09	0.056	0.00	1.80	0
Capillary drive (mm)	0.05	0.025	0.00	0.11	0
Roughness ratio (RFR)	0.38	0.000	0.00	0.12	0

Table 5.2 Classification of the sensitivity of hydrograph parameters to soil characteristics

Parameter	Runoff volume	Peak flow rate	Time to peak	Time to runoff	Time to end
	vol(mm)	P _r (mm/hr)	T _p (min)	T _r (min)	T _e (min)
Soil water content (%)	LS	LS	MS	HS	NS
Hydraulic conductivity (mm/hr)	MS	MS	NS	HS	NS
Capillary drive (mm)	MS	LS	NS	HS	NS
Roughness ratio (RFR)	HS	NS	NS	HS	NS

Note: 0 = Insensitive (NS), 0 0- 0.04= Low sensitive, (LS) 0.04-0.1=Moderate sensitive (MS) and > 0.1 = Highly sensitive (HS)

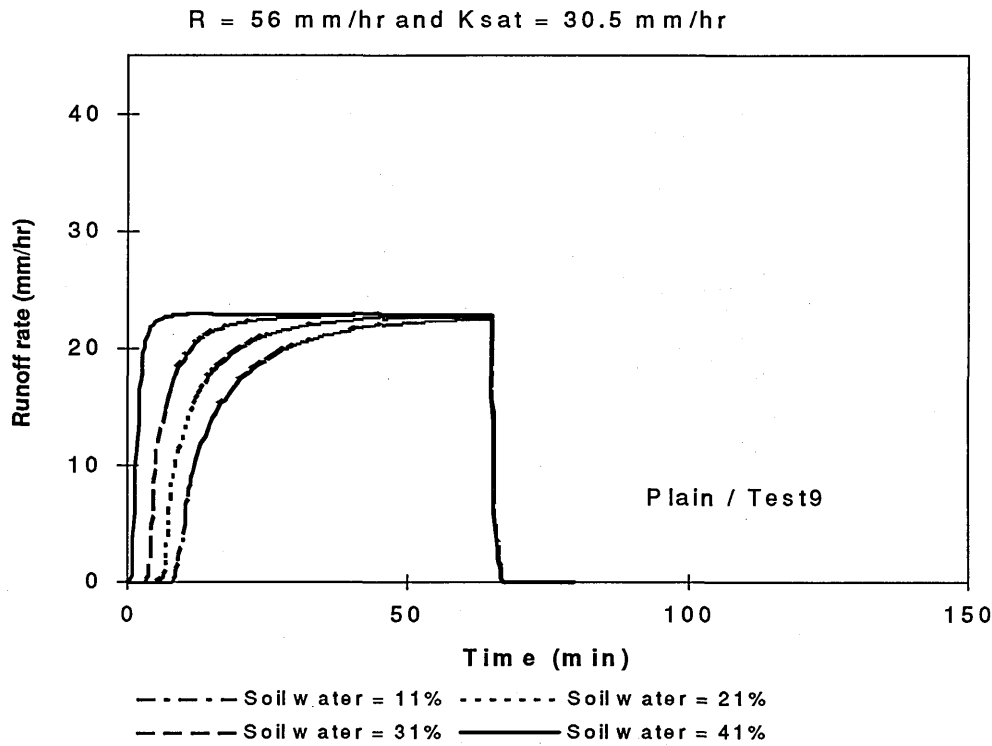


Figure 5.1 Effect of soil water content on runoff hydrograph

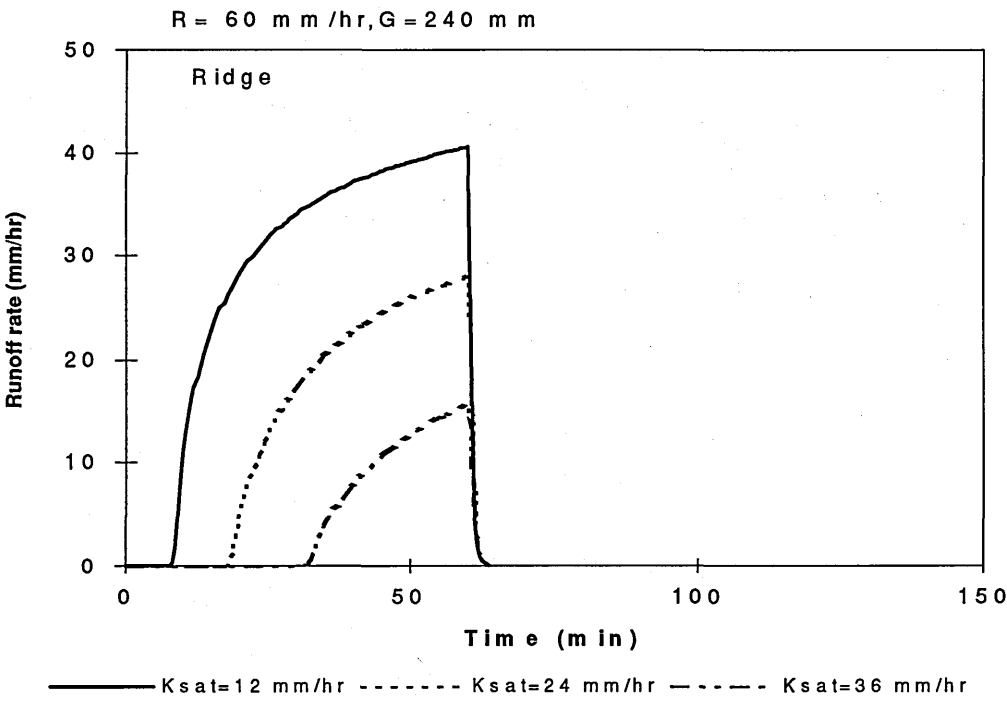


Figure 5.2 Effect of saturated hydraulic conductivity on runoff hydrograph

5.2.4 Effect of capillary drive

Capillary drive is one the main factors that affect runoff hydrograph and output parameters. The sensitivity analysis of output values to changes in capillary drive was also made. The model was run for the capillary drive values of 0, 150, 220, 230 and 240 mm (including the calibrated and recommended values), keeping other parameters constant. Each run was allowed to continue for 63 minutes. According to Table 5.2 the time to runoff is highly sensitive, runoff volume is moderately sensitive, peak flow rate is low sensitive; time to peak and time to end runoff are insensitive to capillary drive (Figure 5.3). Further explanation about this parameter will be discussed later on.

5.2.5 Effect of roughness ratios

In this section the model was tested to see how the changes in the values of roughness ratios along the slope (RFR) and across the slope (ASR) affect the runoff hydrograph and hydrograph parameters (see section 2.4.2). The model was run for a wide range of roughness ratios along the slope (RFR) for example, 1, 12, 24, 28, 30, 32, 34 and 36 percent, keeping other parameters constant (Table 5.1). These values covered the real data measured in the field for simple plane, ridge and furrow; tied furrow and pitting methods for soil and water conservation techniques. Each run was allowed to continue for 140 minutes. This task showed that the sensitivity of runoff volume and time to start runoff to changes in $RFR < 34$ percent was small and $RFR > 36$ was considerable (Figure 5.4). The peak discharge, time to peak and time to end are non-sensitive to changes in RFR values. According to Quinton (1994) the sensitivity of KINEROS modified to EUROSEM to roughness ratio (RFR) is low, especially the peak discharge and time to peak are non-sensitive.

The model was also run for a wide range of roughness ratio across the slope (ASR), for example, 1, 18, 36, 54 and 72 percent at low and high water

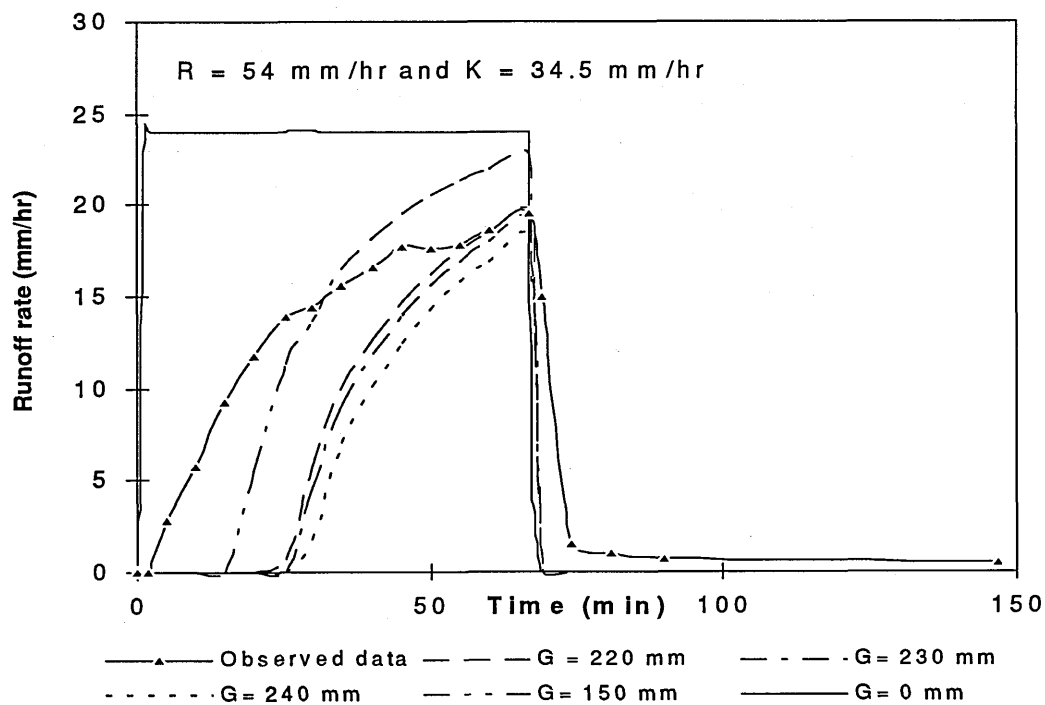


Figure 5.3 Effect of Capillary drive (G) on runoff hydrograph

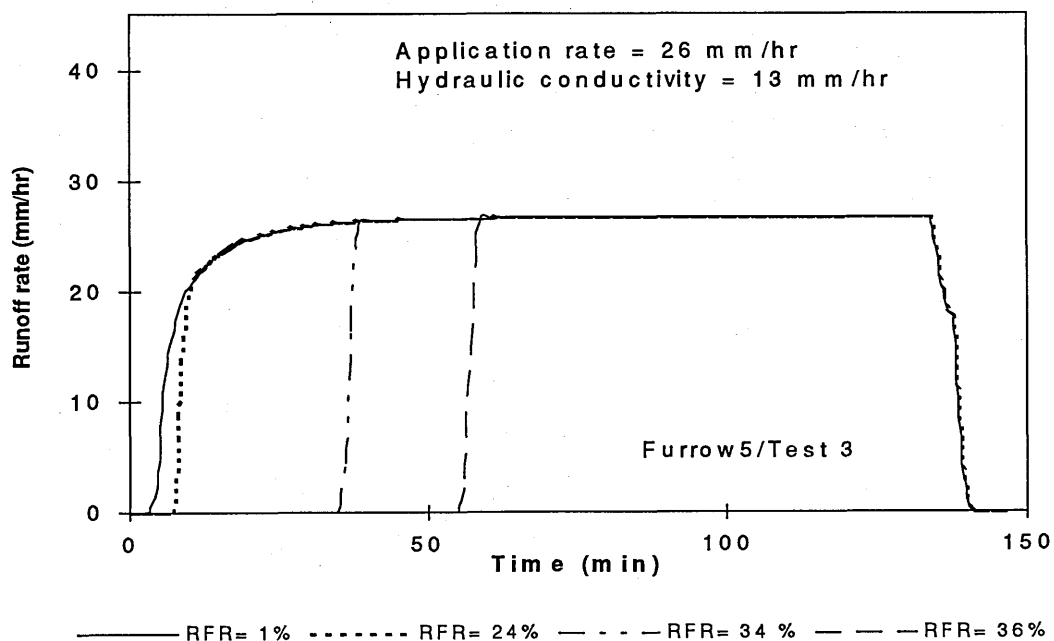


Figure 5.4 Effect of roughness ratio along the slope (RFR) on the runoff hydrograph

application rate (e.g. 46 and 100 mm/hr), keeping other parameters constant. This task showed that the runoff volume is non-sensitive to changes in roughness ratio across the slope (ASR). The sensitivity of other parameters is also negligible. The roughness values were measured in the laboratory and in the field by using a chain meter. The average of resulting values was used in model test.

Overall, the sensitivity analysis showed that the runoff hydrograph was low sensitive to small values and highly sensitive to large values of RFR. The runoff hydrograph was non-sensitive to ASR neither low nor high water application rate.

5.3 Model calibration

Some parameters such as saturated hydraulic conductivity and capillary drive need to be calibrated. Although there is an interaction between these two factors, the hydraulic conductivity values was measured accurately so that it was not necessary to change it so much to match with observed data during the calibration process. Several techniques exist to examine errors in rainfall-runoff models. A number of indices have been developed to compare model-generated hydrographs with measured hydrographs (Walling, 1994). One simple way is to collect data for comparison with predicted results, but this approach is not always practical. Alternatively, leave-Half-out cross-validation or split sample test can be used (Party and Marino 1983, Klemes 1986 and Zao 1995). In this technique, the recorded data (e.g. R events) is randomly split into two halves, one of which should be used for calibration and the other for validation. The calibrated model derived from the first half is used to predict the direct runoff hydrograph for any members of second half. Then the root mean square of error is calculated for any of members of second half. Finally the mean value of the $R/2$ residual mean square errors (RMSE) is calculated as follows:

$$RMSE = \frac{\sum (RMSE(r))}{(R / 2)} \quad 5.2$$

According to Klemes (1986) for a simulation of the effect of a change in climate, the model should be calibrated on a dry climate scenario and then validated on a wet climate scenario and vice versa. This procedure has been used to calibrate the model on low water application rate and then used on high application rate in this study.

The KINEROS-EUROSEM model was calibrated for three types of catchments, ridge and furrows in the field; ridge and furrows and simple plane in the laboratory. Two tests from the field catchment, three tests from ridge and furrow and three tests from simple plane catchments in the laboratory were selected for calibration purposes (Table 5.3). To test the model the same number of data series, with high application rates were used for validation purposes.

5.3.1 Input parameters

Input parameters to the KINEROS-EUROSEM model can be classified into four groups, rainfall, soil, topographic and vegetation parameters. Details of these parameters are presented in Appendix C.2.

All the tests were carried out on bare soil plots in this study. Except the vegetation parameters, all other parameters were measured in the laboratory or in the field. These tests were randomly selected for model calibration. Some parameters such as saturated hydraulic conductivity and effective capillary drive vary spatially and temporally even during a single rain event. So it was difficult to find fixed values for these types of inputs. The calibration

Table 5.3 Soil and water application characteristics of tests for model calibration

Catchment	Slope	Application rate	Hydraulic conductivity	Soil water content
Laboratory:	(%)	(mm/hr)	(mm/hr)	(%)
1- Plane				
Plane 2	4.7	54	47.5	29.6
Plane 7	23.5	54	30.5	31.4
Plane 9	16.5	54	30.5	31.3
2- Ridge and furrow				
Ridge 1	4.7	60	50	31
Ridge 2	16.5	58	43	30
Ridge 3	23.5	61	53	26.3
Field:				
1- Ridge and furrow				
Furrow7/ Test 3	3.3	49	27	22.7
Furrow3/ Test 5	3.3	26	13	22.5

was conducted to find the best suitable values of some parameters to fit the model. Table 5.3 shows the characteristics of eighth tests for model calibration on three micro-catchments, simple plane and ridge and furrow in the laboratory and ridge and furrow in the field.

5.3.2 Parameters for calibration

In order to see what input parameter combination can give a simulation equivalent to the observed figures, some parameters were calibrated, for instance, the effective capillary drive and the saturated hydraulic conductivity. The calibration results obtained seem to be realistic for the majority of the parameters. The calibration gave the values for capillary drive lying out of the range suggested in the KINEROS User Guide (Woolhiser et al 1990). But it

gave the values for hydraulic conductivity in the range found in the laboratory and field measurement and reported in the literature.

5.3.3 Results and discussion

In this section the calibration of the model for two main input parameters, capillary drive and hydraulic conductivity are discussed. The calibration is done for both laboratory and field values of capillary drive and hydraulic conductivity.

5.3.3.1 Effective capillary drive

The KINEROS-EUROSEM model expects a value for capillary drive (G) in order to function properly. Although the capillary drive and hydraulic conductivity can be measured by performing infiltrometer tests, they cannot be found for a catchment as a whole and usually need to be found by calibration (personal communication with Smith, 1996). Typical values of capillary drive and hydraulic conductivity used in KINEROS-EUROSEM User Guide relate to soil types was a clue that some outputs parameters to the model were sensitive to capillary drive and hydraulic conductivity. The effect of saturated hydraulic conductivity and capillary drive on runoff hydrographs were already described in Figures 5.2 and 5.3.

1- First trial

Effective capillary drive (G) is a dominating factor affecting the KINEROS-EUROSEM model. This factor is related to unsaturated hydraulic conductivity and matric potential as described in sections (2.5.3) and (3.13). It is difficult to find unsaturated hydraulic conductivity. So Woolhiser et al (1990) recommended guide values for soil hydraulic characteristics to use as inputs

to the KINEROS model. The same guide values were adopted by Morgan and Quinton (1994) to use as inputs to the EUROSEM model. For instance, the recommended G values for a sandy loam soil are between 98 to 526 mm. To examine the model, the mean value of capillary drive i.e. 240 mm was chosen to put in the model. The results indicated that the simulated runoff hydrograph did not match the observed hydrograph successfully. A rough comparison between predicted and observed hydrographs in Figure 5.3 shows that the runoff rates predicted by the model are underestimated for the rising limb of runoff hydrographs and then they are more or less equal at the peaks. When the rainfall stops the falling limb of the predicted hydrograph drops sharper than the limb of observed hydrographs in all cases. In the other words the detention storage that started from the end of rainfall until the end of runoff is always less than that of the observed runoff hydrograph in all three charts.

Table 5.4 shows the comparison between two predicted runoff hydrographs from a simple plane for $G = 240$ mm and two related observed hydrographs. As indicated in this table, the observed total runoff values are nearly half of the predicted values. Also the predicted time to start runoff is much smaller than the observed one for two typical example of runoff hydrographs. There is not much difference between predicted and observed values of the remaining hydrograph parameters (Table 5.4). Therefore, the disagreement between the observed and predicted parameters indicates that the values presented in the KINEROS User guide are not proper values to use as input in the model at least for a sandy loam soil and for this type of application.

2- Second trial

In this attempt the model was tested for a wide range of values of G other than suggested in the literature. The results show that the effective capillary drive affects the shape of hydrograph, the time to start runoff and the volume of

Table 5.4 Comparison between predicted and observed runoff hydrographs for a simple plane when G = 240 mm

Plane	Hydrograph	Time to start (min)	Time to end (min)	Time to peak (min)	Peak flow rate (mm/hr)	Total runoff (mm)
6	Predicted	1	74	68	19.5	8
	Observed	25	68	67	17.7	16.3
3	Predicted	2	77	65	8.5	3.7
	Observed	28	74	69	7.2	6.3

runoff. As the G value reduces the time to start becomes smaller, the first stage of rising limb of hydrograph becomes steeper, the second stage of limb becomes flatter and the volume of runoff increases. This case is valid for all types of catchments including ridge and furrow in the laboratory and in the field plots (Figure 5.3). As indicated in this graph the predicted hydrograph has the maximum runoff volume for G=0 mm. Although the goodness of fit between predicted and observed hydrographs is not still quite good, there is a large improvement in agreement.

To see how the model matches to observed data calibration was performed for capillary drive and hydraulic conductivity. The calibrated values of saturated hydraulic conductivity and capillary drive were selected so that the calibrated hydrographs visually match the observed hydrographs and the related parameters closely. The calibrated hydrograph was adjusted in a way that the area under it was nearly equal to the area under the observed hydrograph or the residual square error between them to be minimum. The calibration process shows that the model simulation is viable when the capillary drive values lie between 10 to 25 mm (Figures 5.5 and 5.6). Tables 5.5 to 5.7 show the characteristics of observed and calibrated hydrographs for a simple plane and a ridge and furrow in the laboratory; a ridge and furrow catchment in the field. From these tables it can be seen that the time to start runoff is longer

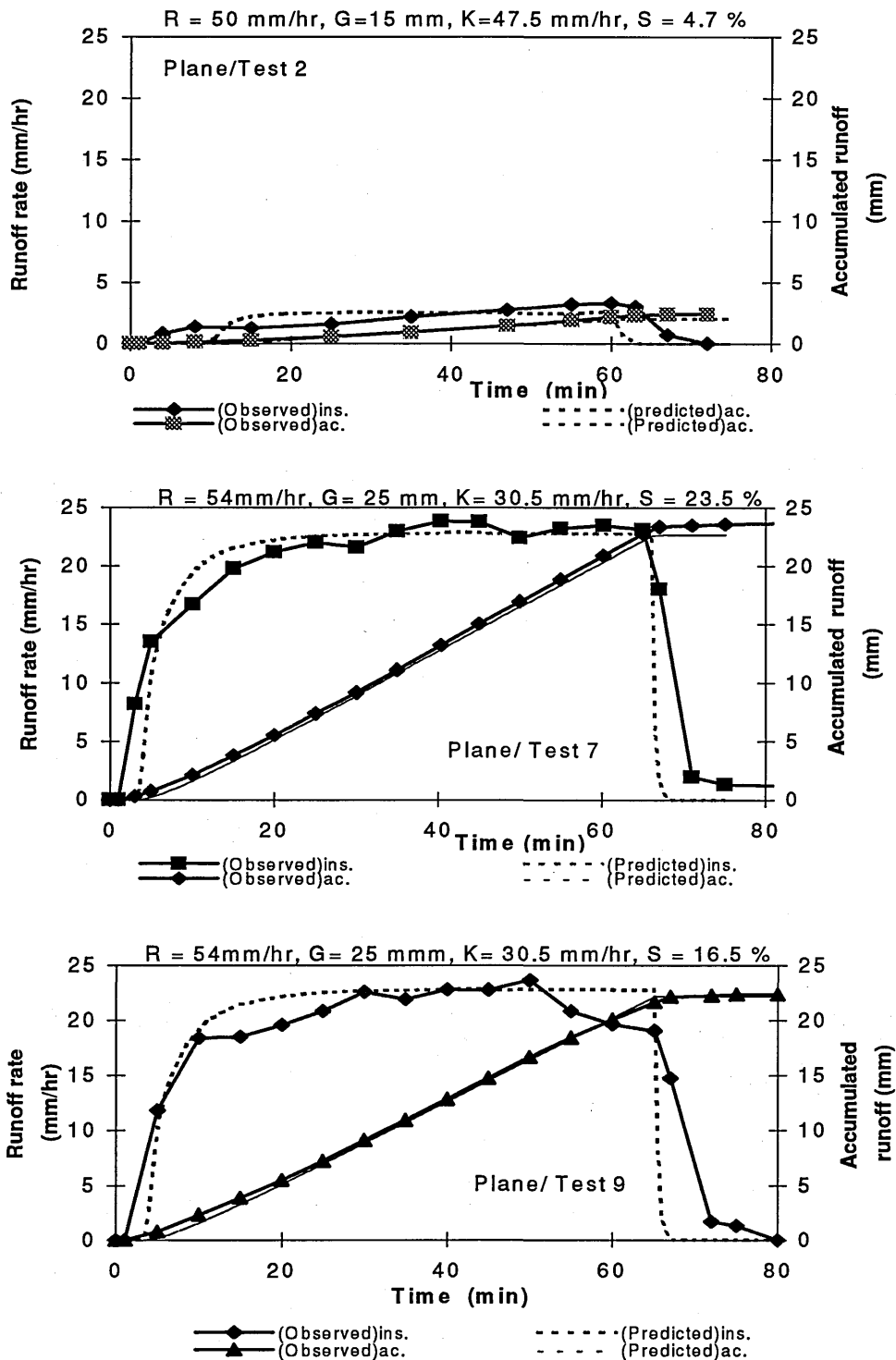


Figure 5.5 Calibration of runoff hydrographs against observed data in the laboratory (simple plane)

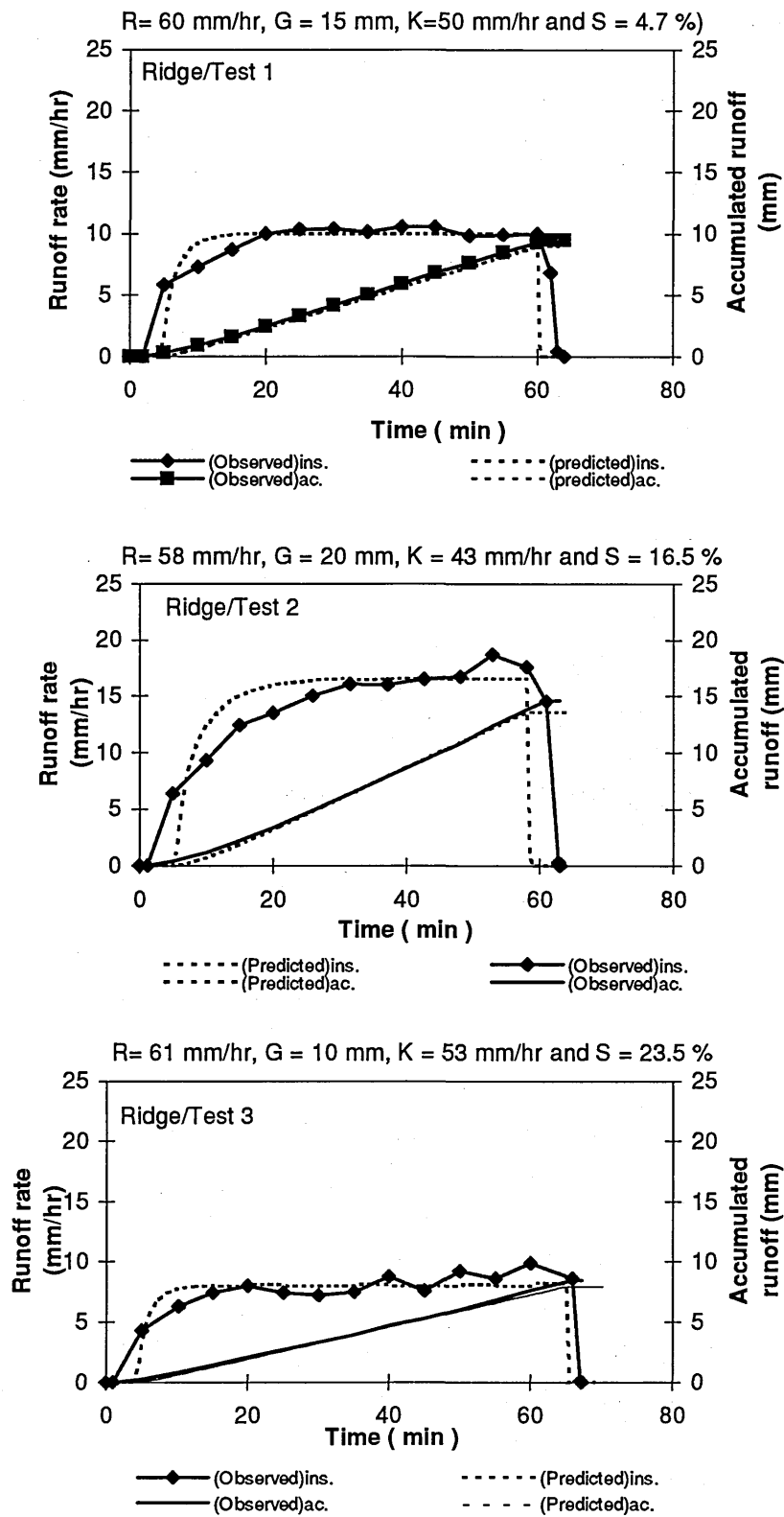


Figure 5.5 Calibration of runoff hydrographs against observed data in the laboratory (ridge and furrow)(contd.)

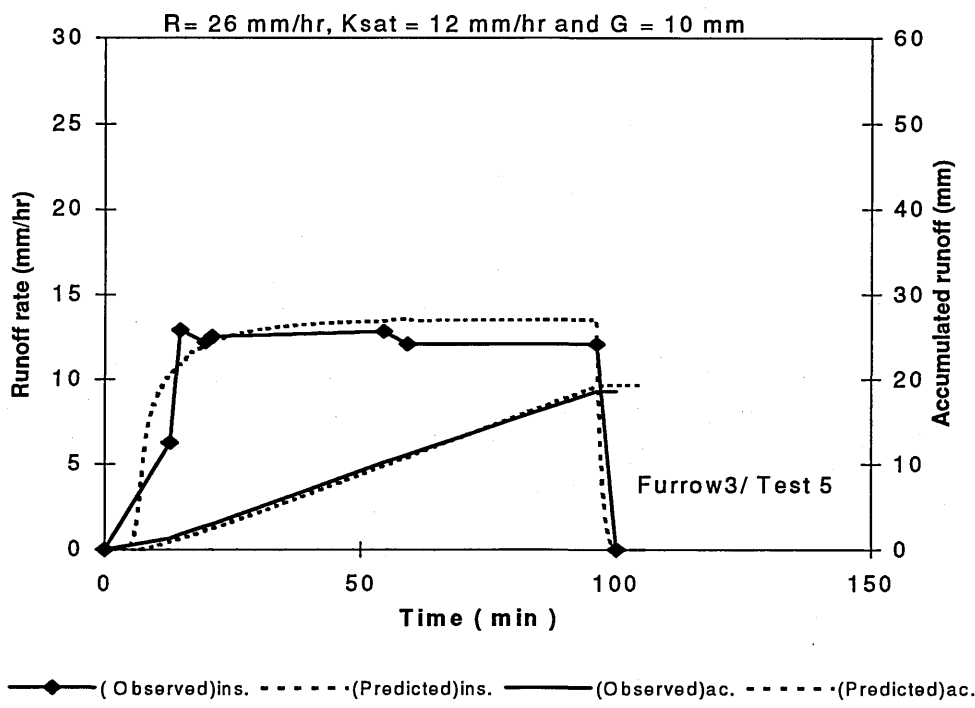
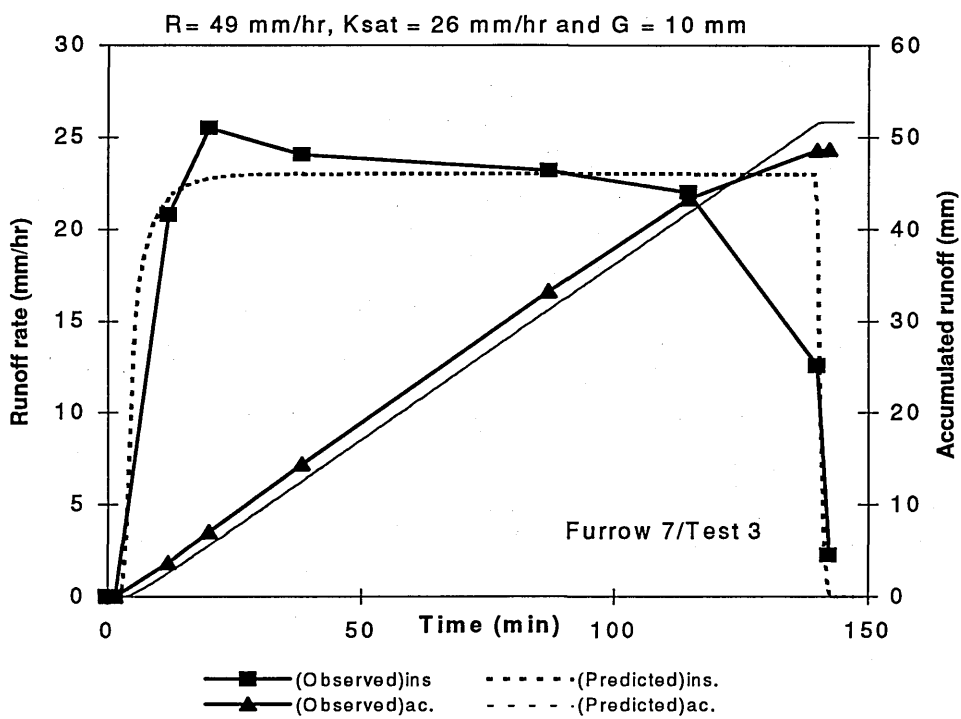


Figure 5.6 Calibration of runoff hydrographs against observed data in the field

Table 5.5 The characteristics of calibrated and predicted runoff hydrographs for a simple plane catchment in the laboratory*

Inputs					Outputs					
Trial	hydrograph	Application rate	**Hydraulic conductivity	Capillary drive	Slope	Time to runoff	Time to end	Time to peak	Peak flow	Volume of runoff
		mm/hr	mm/hr	mm	%	min	min	min	mm/hr	mm
2	Predicted	50	46.7		4.7	1	72	58	3.3	2.5
	Calibrated	50	47.5	20	4.7	10	64	58.5	2.5	2.0
7	Predicted	54	30.1		23.5	1	72	60	23.5	24
	Calibrated	54	30.5	25	23.5	3.5	68	66	23.1	22.6
9	Predicted	54	30.4		23.5	1	72	50	23	22
	Calibrated	54	30.5	25	23.5	3.5	66	66	22.5	22

* All input parameters for predicted and observed runoff are same except the tabulated ones and capillary drive (G) values.
** The real K_{sat} are 46.7, 30.1 and 30.4 mm/hr respectively.

Table 5.6 The characteristics of calibrated and predicted hydrographs of a ridge and furrow in the laboratory *.

Inputs					Outputs					
Trial	Hydrograph	Application rate	**Hydraulic conductivity	Capillary drive	Slope	Time to start	Time to end	Time to peak	Peak flow	Runoff volume
		mm/hr	mm/hr	mm	%	min	min	min	mm/hr	mm
1	Predicted	60	49.5		4.7	1.8	62	40	10.5	9.8
	Calibrated	60	50	15	4.7	4	61	36.5	10	8.9
2	Predicted	58	40.4		16.5	1.2	63	53	18.7	15.3
	Calibrated	58	41.5	25	16.5	5	58	31.5	15.1	13.6
3	Predicted	61	52.4		23.5	1	67	60	10	9.1
	Calibrated	61	53	10	23.5	4	67	61	8.2	8

* All input parameters for predicted and observed runoff are same except the tabulated ones and capillary drive (G) values.
** The real K_{sat} are 46.7, 30.1 and 30.4 mm/hr respectively.

Table 5.7 The characteristics of calibrated and predicted hydrographs of a ridge and furrow in the field*

Inputs						Outputs				
Trial	Hydrograph	Application rate	**Hydraulic conductivity	Capillary drive	Slope	Time to start	Time to end	Time to peak	Peak flow	Volume
		mm/hr	mm/hr	mm	%	min	min	min)	mm/hr	mm
Test3/ furrow 7	Predicted	49	27		3.3	0.5	142	38.2	24.0	47.8
	Calibrated	49	26	10	3.3	3	142	114.5	23	49.9
Test5 / Furrow 3	Predicted	26	13		3.3	0.5	100	54.4	12.8	18.5
	Calibrated	26	12	12	3.3	4	99	59	13.5	19.6

* All parameters are same except the tabulated parameters and capillary drive (G) value.** The real K_{sat} are 27 and 13 mm/hr respectively.

and the time to end runoff is shorter for the predicted hydrographs than for the observed hydrographs respectively in all the charts.

5.3.3.2 Comparing calibrated with observed hydrographs

The calibrated hydrographs have been examined against three series of tests:

- 1- The series that include data collected from a plane micro-catchment in the laboratory (see Table 5.5).
- 2- The series that include the data collected from a ridge and furrow micro-catchment in the laboratory (see Table 5.6).
- 3- The series contain the data collected from the field on a ridge and furrow agricultural catchment (see Table 5.7).

Although there is visually good agreement between the calibrated and the observed hydrographs, further statistical investigation are required to confirm this relationship. According to Table 5.8 the values of RMSE for all the tests undertaken in the laboratory and in the field are less than 4.3 on both a simple plane and a ridge and furrow. The values of regression coefficient are more than 68% and model efficiency values are more than 60% for all the tests

Table 5.8 Statistical techniques to compare the calibrated hydrographs with the observed hydrograph

Type	Laboratory tests						Field tests	
Catchment	Ridge			Plane			Furrow7	Furrow3
	Test1	Test2	Test3	Test2	Test7	Test9	Test3	Test5
No of data =	17	16	18	13	20	19	9	9
Mean square error (RMSE) =	2.03	4.19	2.18	1.34	4.30	3.71	3.18	1.62
Regression coefficient (R^2)=	82.4	72.2	67.7	0.47	0.85	0.87	0.884	0.912
Model efficiency (E) =	0.76	0.629	0.60	-0.485	0.78	0.83	0.905	0.902

(except Test 2 on a simple plane). However, the RMSE value for the test 2 is the least that may compensate the shortage of two other techniques. From this discussion can be concluded that there is good agreement between calibrated and observed runoff hydrographs.

Hydrograph parameters

Although the calibrated runoff hydrographs have been adjusted to have the least error between calibrated and observed hydrographs, further statistical analysis is required to investigate the relationship between hydrograph parameters. To do so the data related to the observed and the simulated hydrograph parameters after calibration are presented in Table 5.9. According to this table the relationship between predicted and observed data are almost equal to 1 in most of the cases. The relative values are the best for the total runoff.

Table 5.10 also shows a summary of statistical analysis of hydrograph parameters such as total runoff, time to peak and peak flow rate. In this table the calibrated hydrograph parameters are compared with observed

Table 5.9 Observed and simulated hydrograph parameters data after calibration

Total runoff	Observed.	2.0	7.9	8.9	13.6	19.6	22.2	22.6	49.9
	Predicted.	2.5	9.1	9.8	15.3	18.5	22.0	23.9	47.8
	Pre./Obs.	1.2	1.1	1.1	1.12	0.94	0.99	1.06	0.96
Peak flow	Observed	3.3	23.5	23	10.5	18.7	10	24.0	12.8
	Predicted	2.5	23.1	22.5	10	15.1	8.21	23.0	13.5
	Pre./Obs.	0.77	0.98	0.98	0.95	0.81	0.82	0.96	0.73
Time to peak	Observed	60	40.3	40	40	53	40	38.2	54.4
	Predicted	25	45	45	29.5	40.5	50.5	38.2	59.1
	Pre./Obs.	0.42	1.12	1.13	0.74	0.76	1.26	1	1.08

Table 5.10 A summary of statistical analysis of hydrograph parameters

Techniques	Volume of runoff	Time to runoff	Time to peak	Time to end	Peak flow rate
Regression coefficient (R)	0.996	0.032	0.017	0.99	0.973
Standard error (s)	0.98	2.08	11.74	3.044	1.376
Model efficiency (E)	0.997	0.98	0.69	0.96	0.953
Root mean square error (RMSE)	1.248	3.648	14.45	5.06	1.555

hydrograph parameters. According to this table there is good agreement between the calibrated and the observed runoff volumes and peak flow rates. This is because the regression coefficients and model efficiencies between them are more than 95 % and the standard errors and mean square errors are less than 1.5. These two parameters are important from the view point of soil and water conservation techniques. The first one shows the volume needed for the soil surface storage and the second one indicates the critical situation which should be avoided to prevent runoff from the soil surface. Table 5.10 also represents a good relationship between the calibrated and the observed time to end. This is because the regression coefficient and the model

efficiency between them are more than 96 % and the standard error and mean square error are less than 5.1. This parameter can be used to design the maximum length of furrow which can be irrigated by the generated runoff without applying more water to the furrow.

Although the table shows a high model efficiency (98 %) and a low standard error and low mean square error between the adjusted and observed time to runoff, the regression coefficient is low. However, the agreement between the calibrated and the observed time to runoff is still good. This situation also shows that one statistical technique does not adequately describe the agreement or disagreement between hydrological processes.

The poorest agreement exists between the calibrated and the observed time to peak. This is because both the regression coefficient and model efficiency are low; the standard error and the mean square error are high. These two last parameters are also important, because the first one can be used to determine the water application time for the pulse irrigation method in which runoff should be avoided and the second one is useful to know when the critical situation will happen. Further investigation is required to know how the model simulates the runoff hydrograph and hydrograph parameters, especially the last two parameters, time to start runoff and time to peak flow rate. This will be undertaken later in the model validation.

Model validation

5.4 Model validation of stationary nozzle line

Developing a model consists of construction, calibration and validation. Validation is an important task. By validation one can assess how well the formulated model can produce future events. If the model performs well in a validation test, then it will be useful in prediction (Zhao et al. 1995).

To assess the performance of KINEROS modified to EUROSEM the operational testing of the model was carried out after model calibration for capillary drive (G) and hydraulic conductivity (K_{sat}) values. In this study Leave-Half-out Cross-Validation (HCV) or split sample test has been used as the validation technique. Further statistical techniques have been used to evaluate the runoff hydrographs and hydrograph parameters such as runoff volume, time to runoff, time to peak, peak flow rate and time to end.

5.4.1 Laboratory experiments

The model was validated using the data collected in the laboratory for stationary conditions. As described in section (4.2) a soil tray of 2000mm×1000mm and 200mm deep was filled with a sandy loam soil and placed under a rainfall simulator to simulate sprinkler irrigation in the laboratory.

Runoff from the soil tray was collected and measured with respect to time. Two drain tubes were installed in the base of the tray to collect water in order to measure the infiltration rate. Tests were conducted on two types of cultivation, a plane sloping surface and ridge and furrow cultivation with furrows running down the main slope. The experimental parameters are summarized in Table 5.11. The experiments were carried out for thirty six events. These included four types of nozzles, three slopes, three ranges of application rates and two cultivation practices. The detail of experimental characteristics are tabulated in Tables 4.1 and 4.2.

Six tests were randomly selected for the model validation. Table 5.12 shows the values of input parameters to the model test which were used for this purpose. These tests were undertaken on a simple plane and a ridge and furrow micro-catchment in the laboratory. In contrast to the model calibration, the tests with high water application rates scenario was used for model

Table 5.11 Experimental parameters for the laboratory tests

Parameters	Values
*Applied water:	
Application rate, R^1 (mm/hr)	20-65, 65-108 and 210-280
Rainfall duration, T_d (min)	60-130
*Soil characteristics:	
Texture	sandy loam
Hydraulic conductivity, k (mm/hr)	6-20, 20-36, 36-64
Initial soil water content, θ_i (%)	4, 24-30, 30-37 %
Capillary drive, G (mm):	10-25
*Cultivation:	
1- Plane surface	
Main slope (%)	3.5, 10, 23.5
Length (mm)	2000
Width (mm)	1000
Height (mm)	200
2- Ridge and furrow:	
Ridge spacing (mm)	900
Ridge height (mm)	200
Side slope (%)	55
Bed slope (%)	3.5, 10, 23.5

1: Note also that R (Irrigation water application rate) is assumed to be constant. This assumes for the purpose of this validation that the sprinkler system is stationary.

Table 5.12 Input parameters to the tests used for model validation

Trial	Application rate	Capillary drive	Hydraulic conductivity	Soil water	Application time
	mm/hr	mm	mm/hr	%	min
Plane:					
Plane 14	151	23.3	19.4	28.8	46.83
Plane 18	277	23.3	14	35.44	46.37
Plane 19	204	23.3	27	34.5	30.83
Ridge and Furrow:					
Ridge 8	235	16.6	46	32.6	60
Ridge 9	214	16.6	29.2	29.7	60.55
Ridge 14	77	16.6	24.8	28.5	61

validation. The average of capillary drive values found in the model calibration was applied to the model validation (Appendix B.2).

5.4.2 Boundary conditions

There are two boundary conditions for the KINEROS-EUROSEM model. The first boundary is when the hydraulic conductivity of soil is equal to the water application rate (or rainfall intensity). In this case the runoff flow rates with respect to water application time should be zero. The second boundary condition is where the surface is impermeable so that there is no infiltration into the soil. In this case, the runoff is equal to the water application. The KINEROS-EUROSEM simulates these two boundary conditions very well.

5.4.3 Comparison between simulated and observed runoff hydrographs

The basis of the comparison between the simulated and observed runoff hydrographs is time to start runoff, time to peak, time to end , peak flow rate, the volume of runoff and runoff hydrographs. The time to start runoff is important, because it is the time of danger and also an index of soil saturation.

Practically this parameter can be used to design sprinkler irrigation systems such as the pulse sprinkler method. The time to peak is also important so that the critical water application time can be estimated to prevent runoff. The peak flow rate is a critical point that should be recognized and taken into account in design and management. The maximum capacity of soil and water conservation techniques such as pitting and micro-basin storage can be determined using the peak flow rate. The number and the total volume of soil and water conservation structures can be determined by using the total volume of runoff. The optimum length for the furrows can be determined by using the total volume and runoff duration. The comparison between runoff hydrographs shows generally how the model simulates the runoff hydrograph and related parameters.

5.4.3.1 Individual tests

In this section each test is discussed individually and a comparison is made between the laboratory results and model simulations. The simulated hydrographs were produced by using the average of capillary drive values resulted from model calibration as input in the model validation. Figure 5.7 show the comparison between observed and predicted runoff hydrographs for individual tests. The values of observed and corresponding simulated hydrograph parameters are also presented in (Table 5.13).

Simple plane

The charts (a), (b) and (c) from Figure 5.7 show the runoff hydrographs from a simple plane at low, medium and high water application rate (151, 204 and 277 mm/hr). As expected these graphs indicate that the high water application

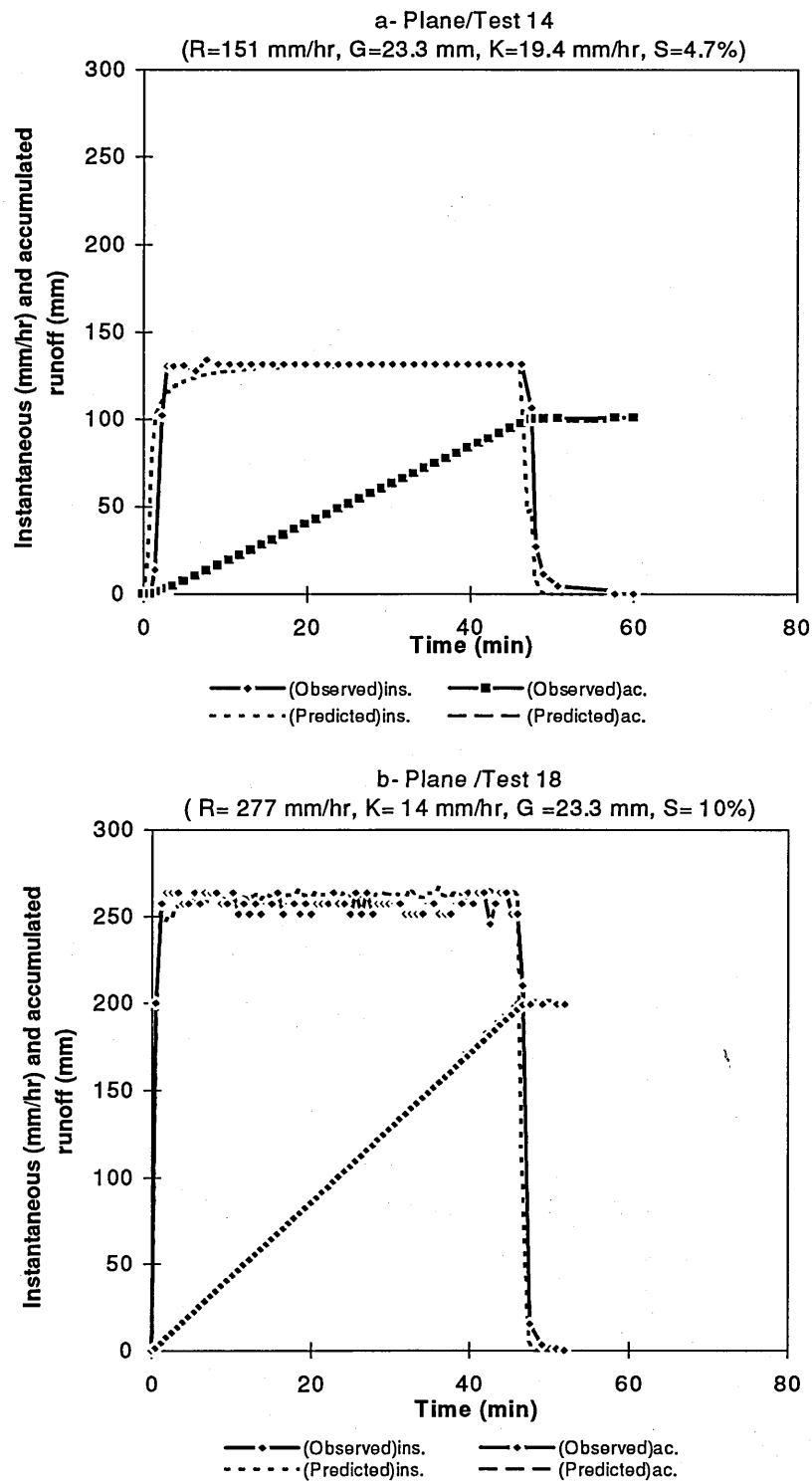


Figure 5.7 Comparison between observed and predicted runoff hydrographs

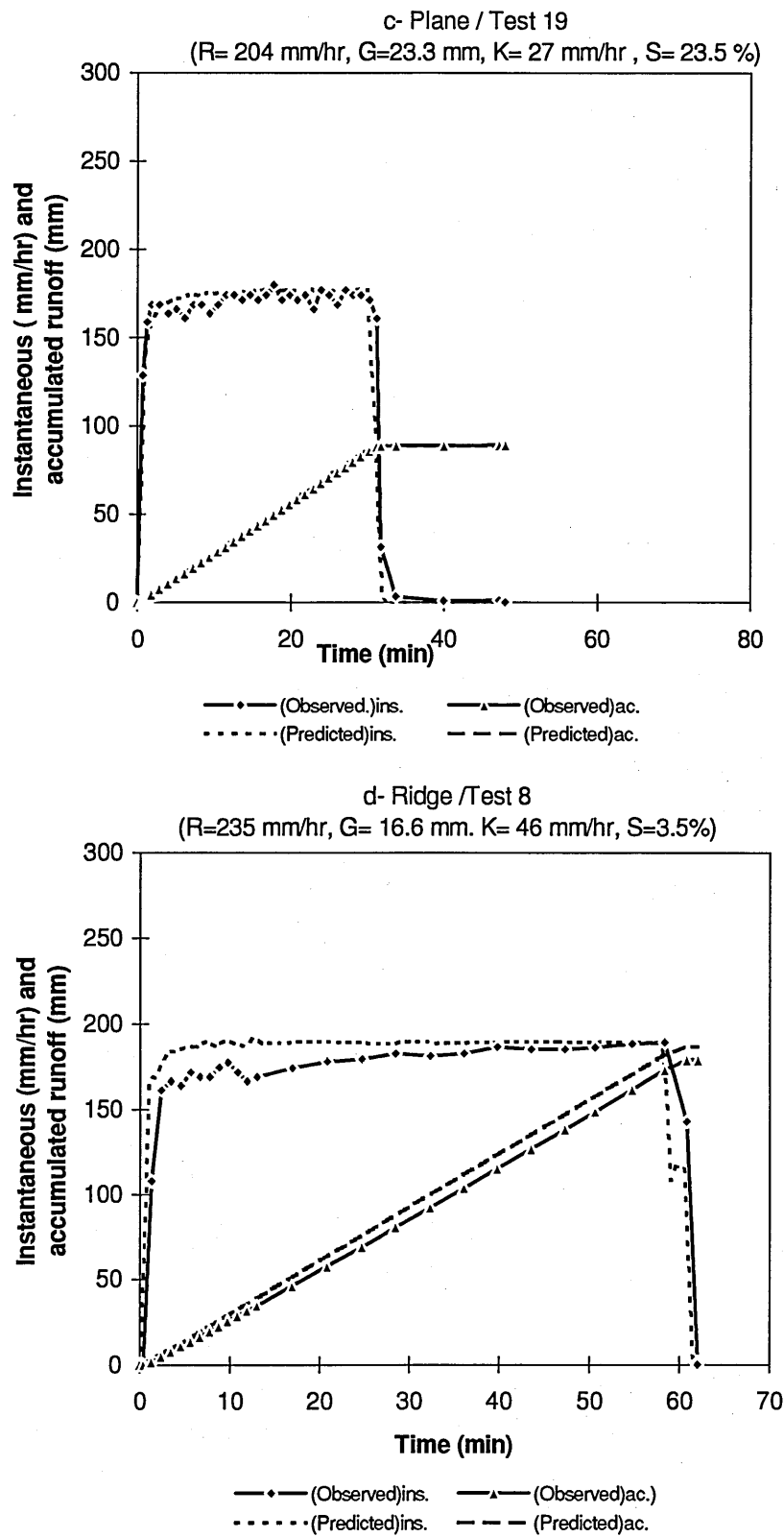


Figure 5.7 Comparison between observed and predicted runoff hydrographs (contd.)

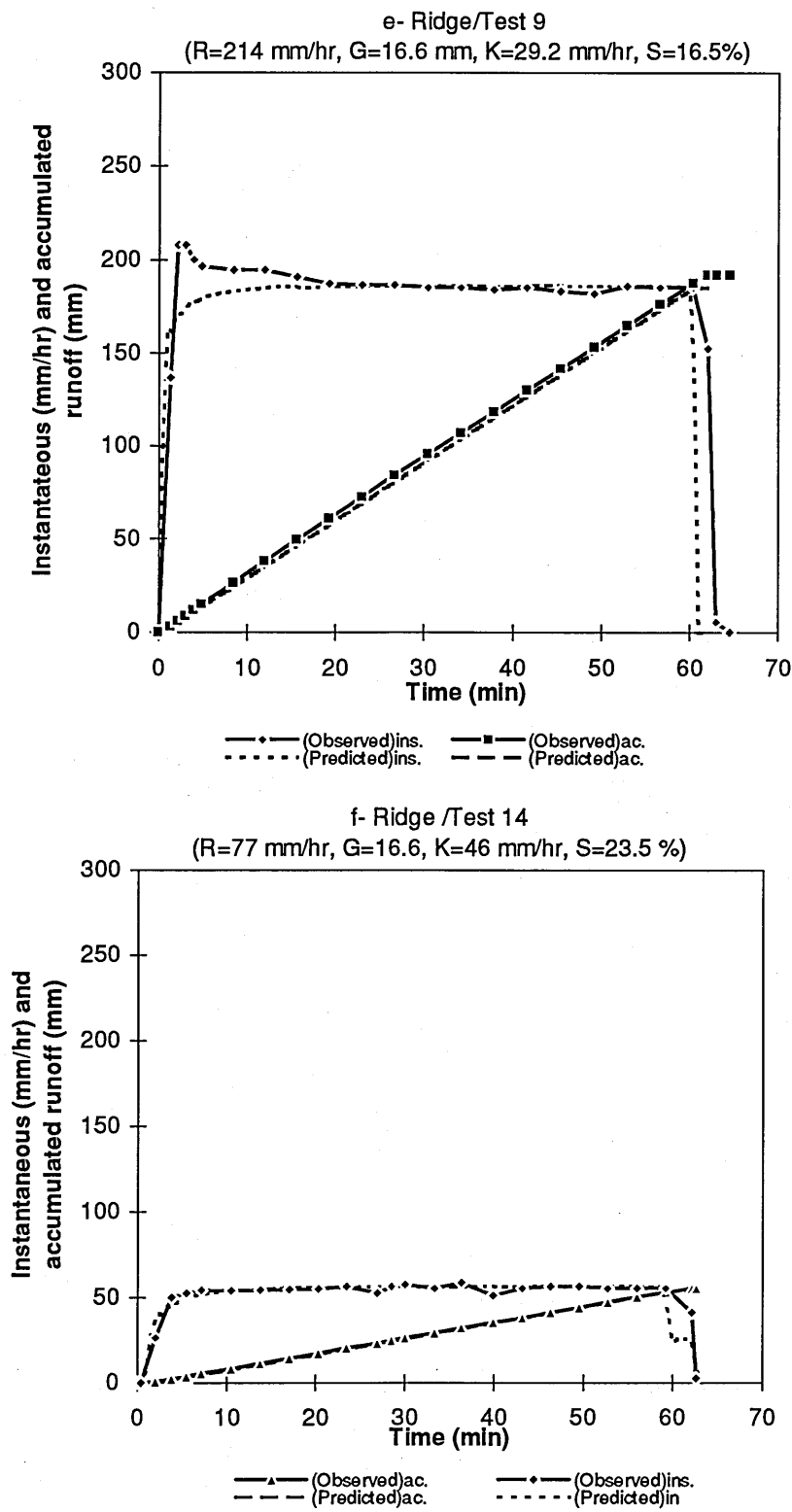


Figure 5.7 Comparison between observed and predicted runoff hydrographs (contd.)

Table 5.13 Parameters describing observed and predicted runoff hydrographs.

No/plot No	Test Type	Average application rate	Hydraulic conductivity (K)	Soil water content	Slope (%)	Capillary drive		Time to peak runoff		Peak rate	Duration of runoff	Total runoff
						(G)	(mm)	(T _r)(min)	(T _p)(min)			
Plane:												
Plane 14	Predicted	124	19.4	28.8	4.7	23.3	1.42	7.72	134.19	57.75	100.8	
	Observed	124	19.4	28.8	4.7	23.3	0	43	131.84	49.5	99.04	
Plane 18	Predicted	277	14	35.4	10	23.3	0	1.83	263.4	52	199.3	
	Observed	277	14	35.4	10	23.3	0	36	266.05	49	201.27	
Plane 19	Predicted	204	27	34.5	23.5	23.3	0	17.7	180	48	88.77	
	Observed	204	27	34.5	23.5	23.3	0	27	178	33.5	88.58	
Ridge and furrow												
Ridge 14	Predicted	77	24.8	28.5	23.5	16.6	0	29	56.7	63	54.5	
	Observed	77	24.8	28.5	23.5	16.6	0.42	36.4	58.7	63	55.2	
Ridge 8	Predicted.	235	46	32.6	3.5	16.6	0.42	60	189	62.02	178.5	
	Observed	235	46	32.69	3.5	16.6	0	58.3	190.9	62	186.5	
Ridge 9	Predicted	214	29.2	29.7	16.5	16.6	0	42.5	186	61	185	
	Observed	214	29.2	29.7	16.5	16.6	0	2.2	208	65	192	

rates generate more runoff than the low water application rates from a simple plane.

Figure 5.7 - chart (a) shows the observed and simulated runoff hydrographs from a simple plane at low water application rates. In both hydrographs, the time to start runoff begins after a short time from the beginning of water application. This is because the initial water content of the soil is high (29%) and the time of concentration is low (i.e. the length of the micro-catchment is short). Obviously, the simulated time to start runoff matches the observed data closely. After that the hydrograph rises sharply and then reaches a steady state as long as the irrigation water is applied. This is because the water application rate does not change and soil hydraulic conductivity reaches an equilibrium position. When the water application stops, the recession part declines sharply and after a short time runoff stops. This is obvious, because the simple plane is sloped (4.7%) and length of plane is short so that the generated runoff is depleted from the soil surface quickly. As can be seen from chart (a) and Table 5.13 visually there is the best agreement between simulated and observed runoff hydrographs and corresponded parameters with the exception of time to peak. Regarding to the time to peak runoff, if the minor differences between the runoff rates are ignored or the average of runoff rates along the steady part of the observed hydrograph are considered, then the simulated and observed time to peak may come closer together. In this chart the accumulated curves show the total runoff at any time. From this graph can be seen that when the water application stops the total runoff increases with a lower rate.

Figure 5.7-charts (b) and (c) show observed and simulated runoff hydrographs for a simple plane at medium and high water application rates. The time to start runoff corresponding to these graphs is much shorter than that of the test (a), this means runoff occurs earlier. This is because the slopes of these two tests (10% and 23.5%) are much steeper than that of test (a) (4.7%). The rising and falling limbs of these hydrographs are steeper than that of test (a). This is

because of the steep slopes and rapid depletion of runoff from the soil surface in both tests. As can be seen from the charts and Table (5.13) the comments on test (a) are also valid for both test (b) and (c). In other words the model simulates the runoff hydrographs and the related parameters very well.

Of particular interest to the model validation is the use of the averaged calibrated capillary drive as an input parameter in model and getting a good simulation.

Ridge and furrow

The charts (d), (e) and (f) from Figure 5.7 show the runoff hydrographs from a ridge and furrow at high and low water application rate. These graphs also indicate that the high water application rates generate more runoff from a ridge and furrow than the low water application rates. Figure 5.7 - chart (d) shows the observed and simulated runoff hydrographs from a ridge and furrow at high water application rates. In this chart the simulated time to start runoff matches the observed data closely. In both hydrographs, the time to start runoff begins after a short time from the beginning of water application. The reason was described in the previous section. However, the time to start runoff for a ridge and furrow is a little shorter than that of a simple plane (Table 5.13). This is because of the lower capillary drive of the ridge and furrow ($G = 16.6$ mm) compared to the higher capillary drive of the simple plane ($G = 23.3$ mm) and the effect of ridge and furrow cultivation on runoff generation. Then the simulated and the observed hydrographs rise sharply. This is because of the high water application rate, high initial soil water content and the ridge and furrow effect. Both hydrographs stay constant for the period of water application time. This is because the water application rate does not change and the soil parameters remain constant during the irrigation event. When the water application stops, both runoff hydrographs decline sharply and after a short time runoff becomes zero. The reasons have been described in the previous

section. According to this graph (d) and Table 5.13 visually there is the best agreement between simulated and observed runoff hydrographs and corresponding parameters with the exception of time to peak. The previous argument about time to peak is also valid for runoff hydrographs (d) resulting from the ridge and furrows. Regarding the time to peak, if the minor differences between the runoff rates are ignored or the average of runoff rates along the steady part of observed hydrograph is considered, then the simulated and observed time to peak match together closely. In this chart the corresponding accumulated curves show the total runoff at any time. However, when the water application stops the total runoff remains constant until the end of runoff. It can be seen from these curves the model simulates the observed total volume successfully.

Figure 5.7 - graph (e) represent the observed and simulated runoff hydrographs from a ridge and furrow at low water application rates. Although the slope of runoff surface related to these graphs is greater than that of charts (d) and (f), the slope of the rising limb of them is not as sharp as that of chart (d) and (f). This is because the water application rate related to graphs (e) is lower.

The time to start runoff corresponding to chart (e) is equal to that of the chart (d) and (f). However, this factor is smaller than that of the test (a) (Table 5.13). This means runoff occurs earlier in chart (e). This is because the hydraulic conductivity of this test is lower and the slope (23.5%) is much greater than that of test (a) (4.7%) (refer to the section 4 for more detail about the parameters effect on runoff hydrographs).

In spite of different slopes, the slope of falling limbs of these hydrographs (charts (d) to (f)) are more or less the same and equal to those of simple plane charts (a, b and c). This may be due to the flowing of runoff from the ridge sides, rising of water level in the furrow and the rapid depletion of runoff from

the soil surface, even in a smaller furrow bed slopes (e.g. 3.5%). The simulated peak flow rates match the observed peak flow rate in all three charts related to the ridge and furrow cultivation. A rough comparison between these graphs also shows that the peak flow rate increases as the water application rate increases and the hydraulic conductivity reduces. There is not a good agreement between observed and predicted time to peak. This can be improved by using the average runoff rates for the steady part of observed hydrographs as described for a simple plane.

5.4.3.2 Overall comments

Figure 5.7 and Table 5.13 indicate that the predicted time to start runoff is close to the observed time to start runoff both for the simple plane and the ridge and furrow. This trend is the same for all hydrographs without exception. However, to see just how significant the discrepancy between observed and predicted time to runoff is, statistical analysis is needed. This is discussed in the next section.

Time to ending runoff is another hydrograph parameter. The model simulates this parameter in all six experiments undertaken on a simple plane and ridge and furrow very closely. Duration of runoff is another parameter which can be determined by subtracting the time to ending runoff from the time to start runoff. Therefore, the magnitude of this parameter is highly related to the two previous parameters. Regarding the discussion about two previous parameters, agreement between observed and predicted duration of runoff is also satisfied.

A comparison between observed and simulated time to peak runoff shows lower predicted values for predicted time to peak runoff in all the experiments, with the exception of Test 14 (Table 5.13). So there is not a good agreement between them. This may be improved by using the average of runoff rates occurring on the steady part of observed runoff hydrographs. Perhaps the lower

predicted values for time to peak runoff can be considered as a positive point in irrigation system design.

Runoff volume can be determined by measuring the areas under the instantaneous observed and simulated runoff hydrographs or accumulated curves. The data presented in Table 5.13 and Figure 5.7 show the simulated values are close to observed data for all the tests and visually there is good agreement between them.

The magnitude of peak flow rate mainly depends on water application rate, hydraulic conductivity and capillary drive. A comparison between six charts (a to f) shows that the peak flow rate is also simulated for a wide range of effective parameters very well.

Overall, there is visually good agreement between the simulated and observed runoff hydrographs and corresponded parameters for stationary sprinkler conditions. This includes both simple plane and ridge and furrow practices tests in the laboratory. Of particular interest to the model validation is the use of the average calibrated capillary drive values as input parameters in the model and getting good simulations. Therefore, the model can predict runoff and the related parameters very well. Further statistical analysis is required to confirm this discussion.

5.4.4 Statistical analysis

Correlation analysis, residual mean square error and the model efficiency techniques were used to analyze the data in this study. In these techniques, the simulated hydrographs data and hydrograph parameters are compared to the observed hydrographs data and hydrograph parameters. Further tests carried out by comparing the calculated correlation coefficient with the standard

test tables. The confidence intervals of the best fit lines, slopes and intercepts were determined at the level of 95%.

5.4.4.1 Hydrograph analysis

A summary of the statistical analysis of hydrographs are presented in Table 5.14. Model efficiency is one of the indices of comparison between observed and predicted runoff data in this table. The model efficiency values are more than 94% for most of the cases and 84% for one case. Therefore, these values are close to the slope of 1:1 line. So the model simulates observed data properly. The regression analysis confirms this argument, because the regression coefficients (R^2) are more than 90% and also more than tabulated values which can be found in the standard tables. T-test showed that there is not a significant difference between the slope and the intercept of each regression line compare to slope = 1 and intercept = 0 respectively. The root mean square error is another criteria that indicates the amount of errors resulted from comparison between the predicted and the observed data that are less than 22% that can be reasonable. Figure 5.8 also shows the correlation lines together with the 95% confidence limits between observed and predicted runoff hydrographs. These lines give more confidence to the data that can be encountered into regression line with a high probability.

Overall, the model simulates the observed data for both ridge and furrow and simple plane in a stationary condition successfully.

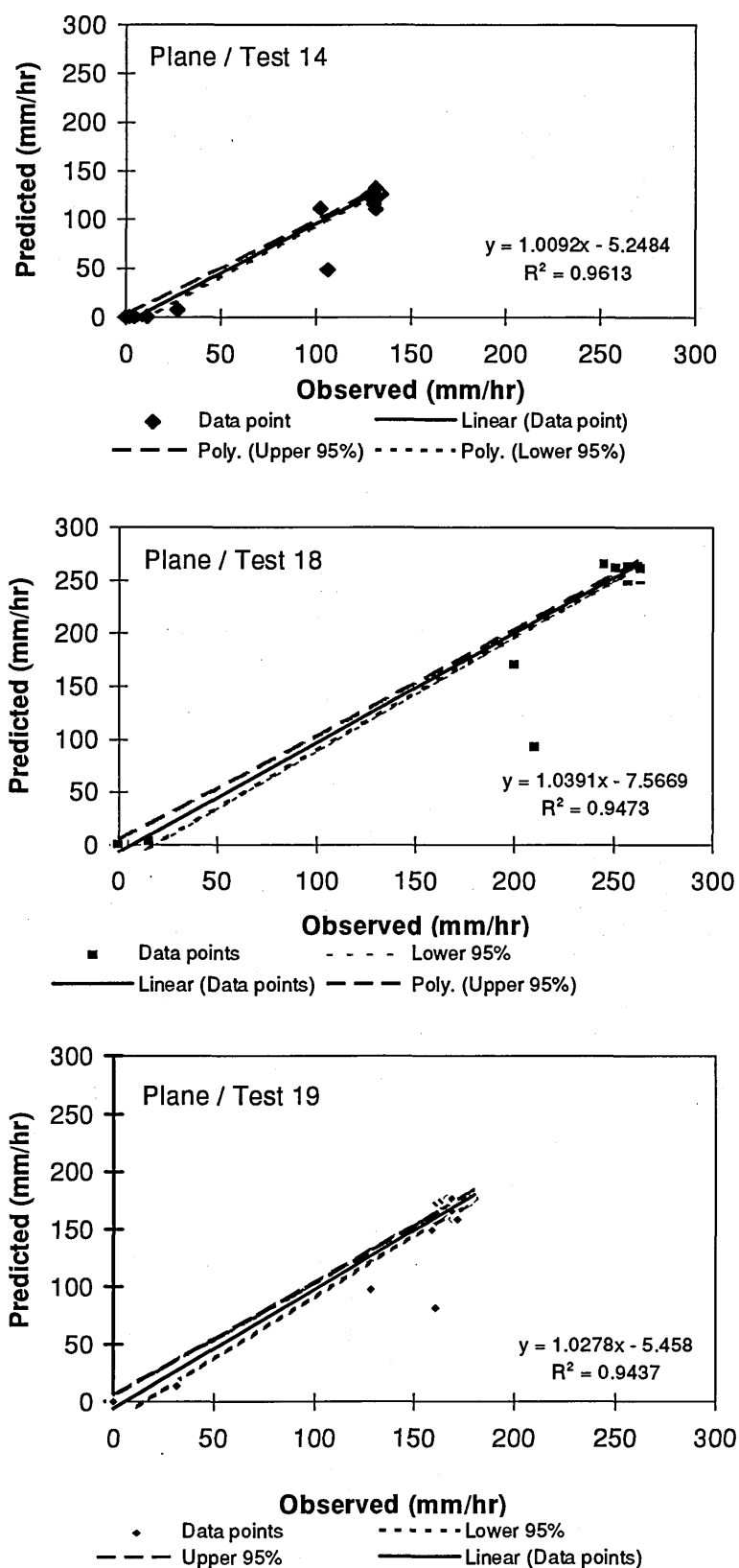


Figure 5.8 Correlation between observed and predicted runoff

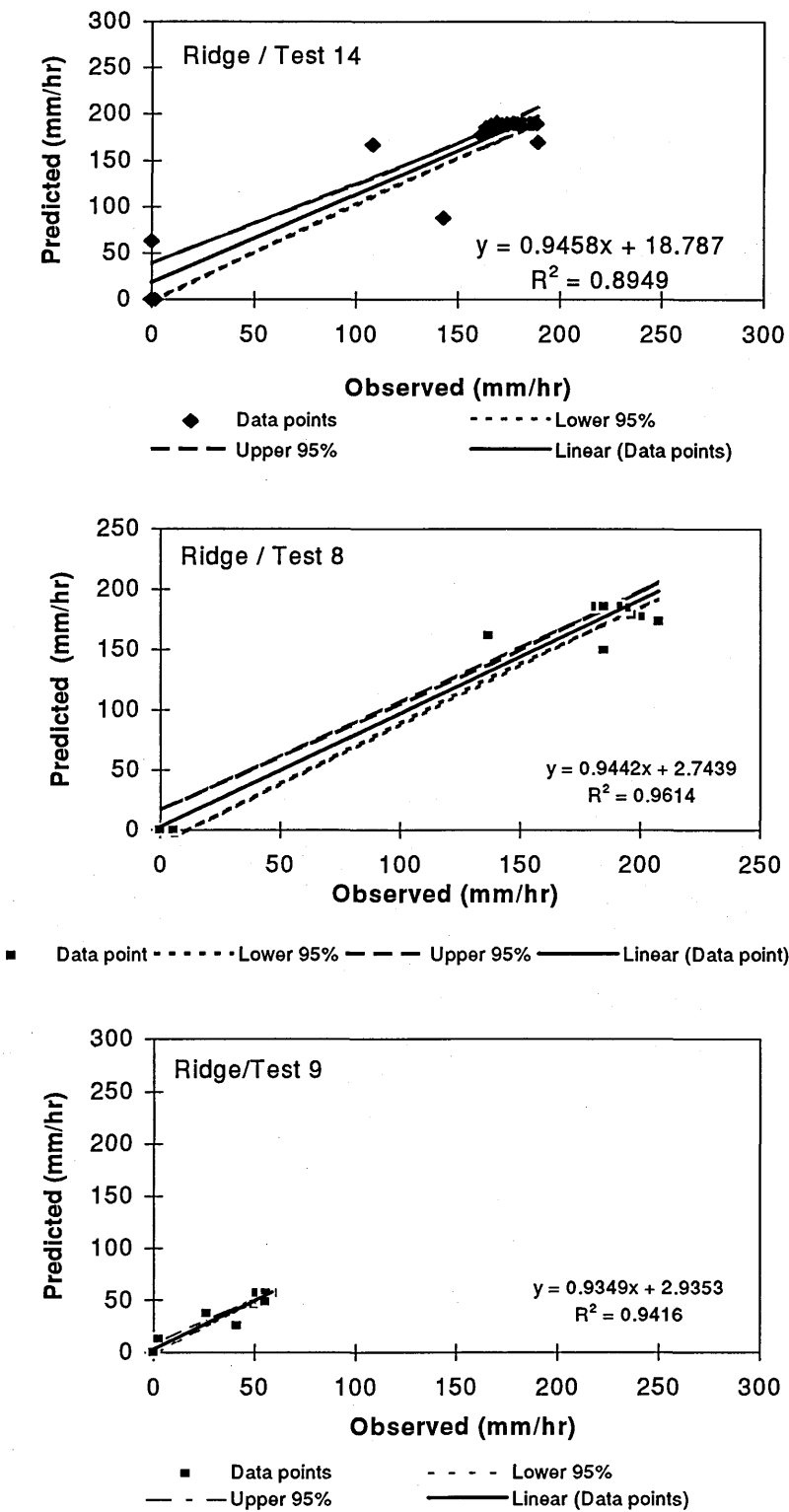


Figure 5.8 Correlation between observed and predicted runoff (contd.)

Table 5.14 A summary of statistical analysis of observed and predicted runoff for stationary conditions

Test	Error	Coefficient of efficiency technique			Correlation analysis technique		
		RMSE	(F1) =	(F2) =	E	Correlation coefficient (R ²)	
		Root mean square error	Σ(predicted-observed) ²	Σ(Observed-mean observed) ²	Efficiency	Equation	Calculated No of Tabulated data
Plane:							
Test 14	10.82	5037.5	92289.8	0.945	y = 1.0092x - 5.2484 0.956 43 0.288		
Test 18	16.15	18787.1	301260.0	0.938	y = 1.0391x - 7.5669 0.9473 72 0.229		
Test 19	15.42	8797.9	136669.2	0.936	y = 1.0278x - 5.458 0.9437 37 0.317		
Ridge and furrow:							
Test 14	4.82	603.9	10328.2	0.942	y = 0.9349x + 2.9353 0.9416 26 0.374		
Test 8	22.81	15086.0	108695.1	0.861	y = 0.9458x + 18.787 0.8949 29 0.355		
Test 9	14.81	5486.0	144338.3	0.962	y = 0.9442x + 2.7439 0.9614 24 0.381		
Slope (a1)							
		Intercept (a0)			Standard error		
		Main value	Lower 95%	Upper 95%	Main value	Lower 95%	Upper 95% s
Plane:							
Test 14	1.0092	0.947882	1.083056	-5.2484	-14.118	1.990087	10.117
Test 18	1.0391	0.980643	1.097537	-7.5669	-21.978	6.844141	16.085
Test 19	1.0278	0.941646	1.1139	-5.458	-18.8109	7.894794	15.684
Ridge and furrow:							
Test 14	0.9349	0.836786	1.033014	2.9353	-1.89242	7.762983	4.831
Test 8	0.9458	0.817822	1.073815	18.787	-1.76969	39.34317	20.567
Test 9	0.9442	0.860569	1.027807	2.7439	-11.5958	17.08363	13.909

5.4.4.2 Hydrograph parameters analysis

These parameters are: time to runoff, time to peak, peak flow rate, time to end and total runoff. Figure 5.9 shows the correlation lines together with 95 % confidence limits between observed and predicted hydrograph parameters. The hydrograph parameters have been analyzed by the same statistical techniques used for the hydrograph analysis. A summary of the statistical analysis of hydrograph parameters is presented in Table 5.15.

Time to runoff is one the parameters that describes the runoff hydrographs. According to Table 5.15, although the model efficiency for time to runoff is low, it does not adequately describes the model operation. However, the regression coefficient is high ($E=1$) and root mean square error ($RMSE = 0.2$) is low. Therefore, these two indices indicate that the model simulates the time to runoff adequately.

Time to peak is another characteristics of runoff hydrograph. The statistical analysis shows that although the regression coefficient for time to peak is high, the model does not simulate the time to peak. This is because the regression coefficient is negative, the model efficiency is low and residual mean square error is very high. This may be improved by using the time to the average of low rates on the steady part of observed hydrograph or ignoring the little changes in the predicted time to peak and considering a time to suitable flow rate close to the observed peak value.

The next parameter is the time to end which shows also the duration of runoff when it is subtracted from the time to runoff. The correlation between observed and predicted the time to end is shown in Figure 5.9 (part a). It can be seen in Table 5.15 that the model efficiency for this parameter is high ($E= 0.85$), the regression coefficient is also high ($R^2= 0.93$) and residual mean square error is

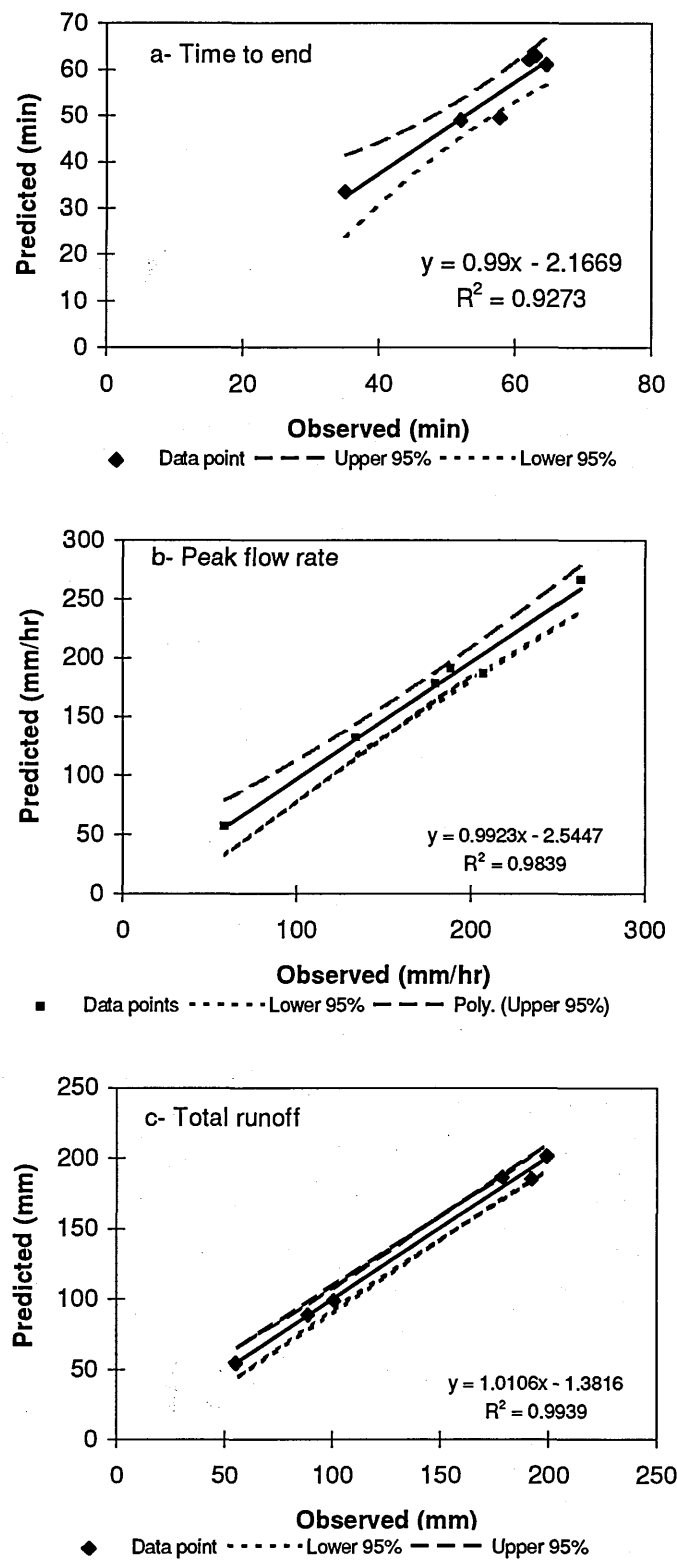


Figure 5.9 Correlation between observed and predicted hydrograph parameters

Table 5.15 Statistical analysis of hydrograph parameters

Parameters	Symbol	Unit	Coefficient of efficiency technique	Root mean square error		
				(F1) =	(F2) =	RMSE
				$\Sigma(\text{predicted-observed})^2$	$\Sigma(\text{observed-mean observed})^2$	Efficiency
Time to runoff	Tr	min		2.37	1.52	0.359
Time to peak	Tp	min		6279.6	2539.1	0.596
Peak flow rate	Qp	mm/hr		482.1	24247.8	0.980
Time to end	Td	min		92.1	618.3	0.85
Volume of runoff	Qv	mm		120.5046	18947.15	0.994

Correlation analysis technique:									
Equation	Slope (a1)		Intercept (a0)			Correlation coefficient			
	Main value	(Lower limit) _{95%}	(Upper limit) _{95%}	Main value	(Lower limit) _{95%}	(Upper limit) _{95%}	Calculated	Tabulated	
$y = -0.4642x + 41.272$	-0.4642	-0.75799	-0.1704	41.272	32.6998	49.84505	1.00	0.707	
$y = 0.9923x - 2.5447$	0.9923	0.816042	1.1686	-2.5447	-34.8966	29.80724	0.8279	0.707	
$y = 0.99x - 2.167$	0.99	0.605249	1.374781	-2.16694	-23.9603	19.62638	0.9839	0.707	
$y = 1.0106x - 1.3816$	1.0106	0.900843	1.120296	-1.3816	-17.5039	14.74071	0.927	0.707	

low (RMSE= 7.7). Therefore, the predicted time to end matches the observed time to end well.

Peak flow rate is the next parameter that describes the runoff hydrograph. The correlation between observed and predicted peak flow rate is shown in Figure 5.9 (part b). According to Table 5.15 the efficiency of model and regression coefficient for the peak flow rate are high ($E= 0.98$ and $R^2= 0.98$). It is concluded that the model simulates the observed data successfully.

The last parameter is total runoff. This parameter can be estimated from the area under the hydrograph or using the accumulated curve. The correlation between observed and predicted total runoff is shown in Figure 5.9 (part c). The statistical analysis shows a good relationship between the observed and the predicted total runoff (runoff volume). This can be recognized from Table 5.15 in which the values of model efficiency is high ($E= 0.99$) and regression coefficient is also high ($R^2= 99\%$) and low root mean square is low (RMSE= 10).

Overall, the model simulates all the hydrograph parameters such as time to runoff, peak flow rate, time to end and total runoff except time to peak.

5.5 Summary

During the model calibration phase:

1- The calibrated values of the effective capillary drive were found to be in the range of 10 to 25 mm for a sandy loam soil. These values match closely the computed values using the time to ponding method.

The calibrated values of hydraulic conductivity were found to be in the range of 12 to 52 mm/hr. The small values are for the earlier and the big values are for the later irrigation events during the cropping season. These are in the

range calculated in this study and recommended in the literature for a sandy loam soil.

2- Visual inspection and statistical analysis techniques confirm that there is good agreement between the calibrated and the observed runoff hydrographs. T-tests indicated that there is no significant difference between observed and predicted data at the level of 99 %.

3- Looking at the hydrograph parameters. This showed that the time to start runoff is longer and the time to end runoff is often shorter for the calibrated hydrographs compared to the observed hydrographs. The reason for these might be due to derivation of KINEROS-EUROSEM model for the relatively large watershed areas in which the time of concentration is more than that of micro-catchment.

There is good agreement between observed and calibrated time to runoff, total runoff, time to end and peak flow rates. However, this agreement is poor between the observed and the calibrated time to peak values.

T-tests proved that there is no significant difference between calibrated and observed time to runoff, time to peak and peak flow rate, volume of runoff and time to end. Therefore, the model simulates the observed hydrograph parameters well.

During the model validation phase:

1- The average values of calibrated capillary drive and saturated hydraulic conductivity were applied as inputs to the model validation. Generally, this produced a good relationship between observed and predicted runoff hydrographs.

Of particular importance to sprinkler irrigation management is the time when runoff begins, the time it takes to reach the peak, the peak discharge, the volume of runoff and the time to end. This information could influence the field manager's decision about how much water to apply at one irrigation and the extent to which he might wish to change the cultivation practice to control the runoff. Fortunately there is visually and statistically close relationship between almost all observed and simulated parameters. This means that under a wide range of validation conditions the model simulates these factors successfully. The relationship between observed and predicted time to peak flow rate is poor. This may be improved by using the time to the average of flow rates on the steady part of hydrograph or ignoring the little changes in the predicted time to peak and considering a time to a suitable flow rate close to observed peak value.

2- Among the hydrograph parameters low correlation and maximum standard error exist between observed and the predicted time to peak. However, the T-test indicated that the discrepancy between predicted and observed data was not significant in each experiment. This was because, the slope of best fit line and the intercept value were not significantly different from unity and zero respectively.

3- Overall, the model is viable to predict surface runoff under static spray conditions in the laboratory for both a simple plane and a ridge and furrow cultivation. Field experiments are required to further validate the model. This is discussed in the next section.

CHAPTER 6

MODEL VALIDATION FOR STATIONARY CONDITIONS IN THE FIELD

6. Model validation for stationary conditions in the field

6.1 Introduction

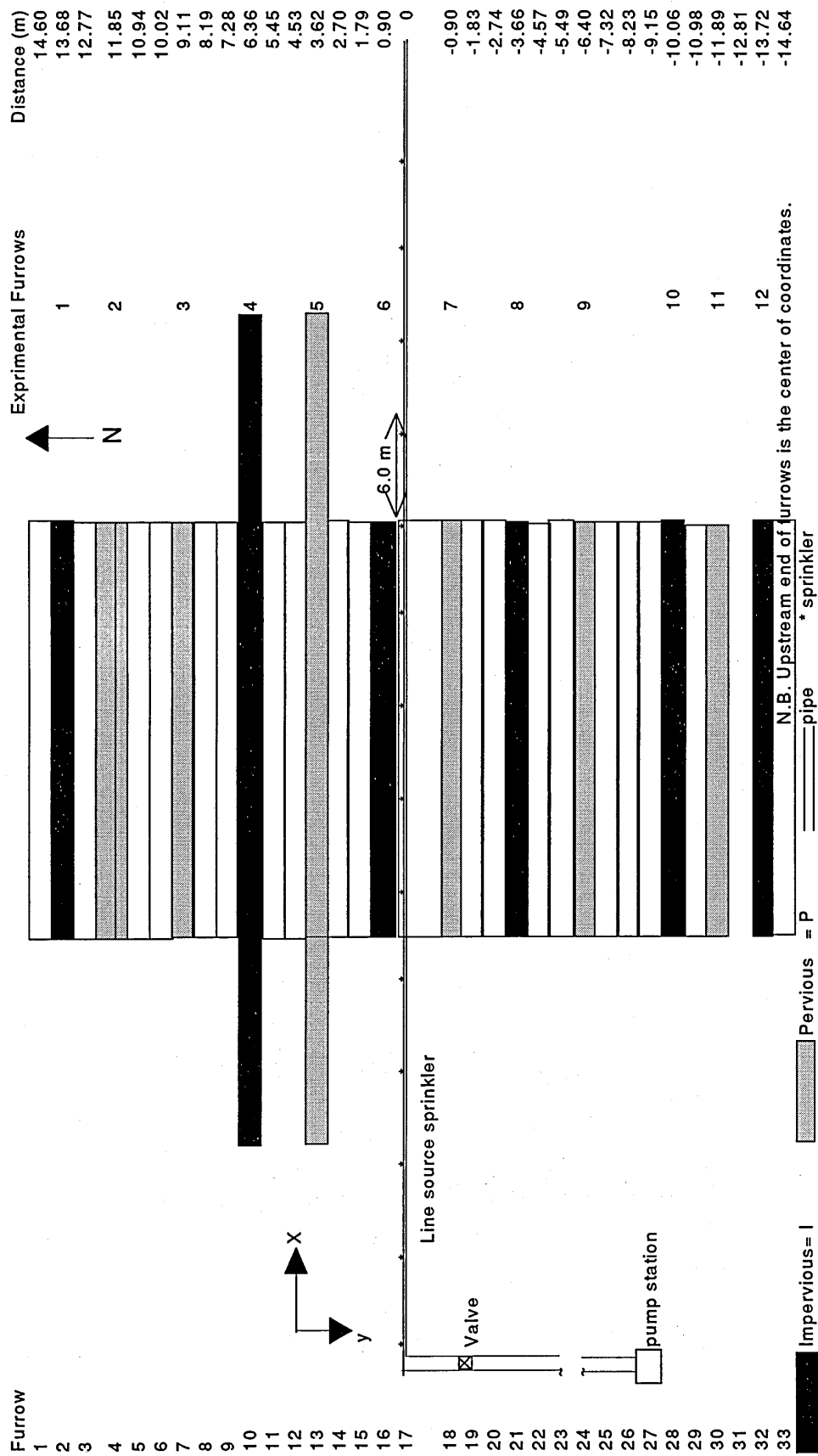
These experiments were undertaken in the field using sprinkler irrigation on a ridge and furrow cultivation system, as a means of collecting data for a field validation of the model for stationary sprinkler conditions.

6.2 Field site

The tests were carried out on an area of land $30\text{m} \times 50\text{m}$ and a bare soil with the slope 3.3% located in the Sand Pit field at Silsoe College. The soil texture is a sandy loam for the first 400mm which changes to sandy silt loam and sandy soil deeper in the soil profile. Some plant residues and stones were also found in the profile. The soil average bulk density is 1.5 g/cm^3 and it was determined by taking three samples from the soil profile. The soil was ploughed and ridged before the tests were run.

6.3 Line source sprinkler system

A line source sprinklers system was laid out in the middle of the site (Figure 6.1). This was used to apply water to the experimental area. The line source produces a water application rate which is uniform along a line parallel to the line source and changes across the line uniformly (Hanks et al 1976 and Willradson et al 1987). To obtain the triangular shape profile of water distribution, the sprinklers should be closely spaced at approximately 10% of wetted diameter or closer and be operated at the design pressure under low wind conditions. A reasonable spacing is up to 20 to 25 percent of wetted diameter. Application rate and system flow change inversely with sprinkler



spacing. Good uniformity along the line source can be achieved under calm conditions and closer spacing (Hanks et al 1976, Morgan and Carr 1988). However, the closer spacings increase the application rate (Willardson et al 1987). A spacing of 3m was chosen for these experiments in order to achieve sufficiently high application rates. This was done by using two parallel line sources, because only 6 m length of sprinkler pipes were available (Figure 6.2).

6.3.1 Experimental procedure

As indicated in the layout of experiments (Figure 6.1) the tests were performed on a site by selecting 12 ridge and furrows. Half of the them were lined by polythene to prevent soil infiltration. These furrows were used to collect the runoff data in order to achieve the following objectives:

- a- to understand the trend of runoff hydrograph for impervious furrow situations,
- b- error and the loss control in field experiments,
- c- data collection from impervious furrow conditions for model evaluation,
- d- depression storage determination.

The remainder were kept unlined and were used to measure surface runoff for model validation. The dimensions and the location of experimental plots are presented in Table 6.1 and the details of tests are illustrated in Appendix D.1.

Two types of sprinklers Rain Bird and Wright Rain with the different nozzle sizes were tested on the grass land. Although the twin Rain Bird sprinkler nozzles were found to have the highest water application uniformity, the Right Rain sprinklers type (twine nozzles) were used for the main experiments. This was because of the existence of these type of sprinklers in the store. The sprinklers were arranged to have spacing between 3 to 6 m. The characteristics of nozzle are presented in Appendix D 1.

A grid of catch cans with the distances of 3m along the line source and 2.75m across the line source were used to measure the water application (Figure 6.2). The application rate at each point was determined by dividing the volume of collected water to the catch can area. According to Morgan and Carr (1988), application rate in strips parallel to the sprinkler line are highly uniform, except in windy conditions.

Table 6.1 Dimensions and location of experimental furrows

Top width = 900 mm				
Bed width = 200 mm				
Side slope = 56%				
Depth = 200 mm				
Furrow No	Type	Furrow Length (m)		Distance from line source (m)
		Test 1 to Test 5	Test 6 to Test 7	
1	Impervious (I)	12.3		13.72
2	Pervious (P)	12.3		11.90
3	P	12.3		9.15
4	I	12.3	24.3	0.640
5	P	12.3	24.3	3.66
6	I	12.3		0.91
7	P	12.3		-0.91
8	I	12.3		-3.66
9	P	12.3		-6.40
10	I	12.3		-10.10
11	P	12.3		-11.90
12	I	12.3		-13.65

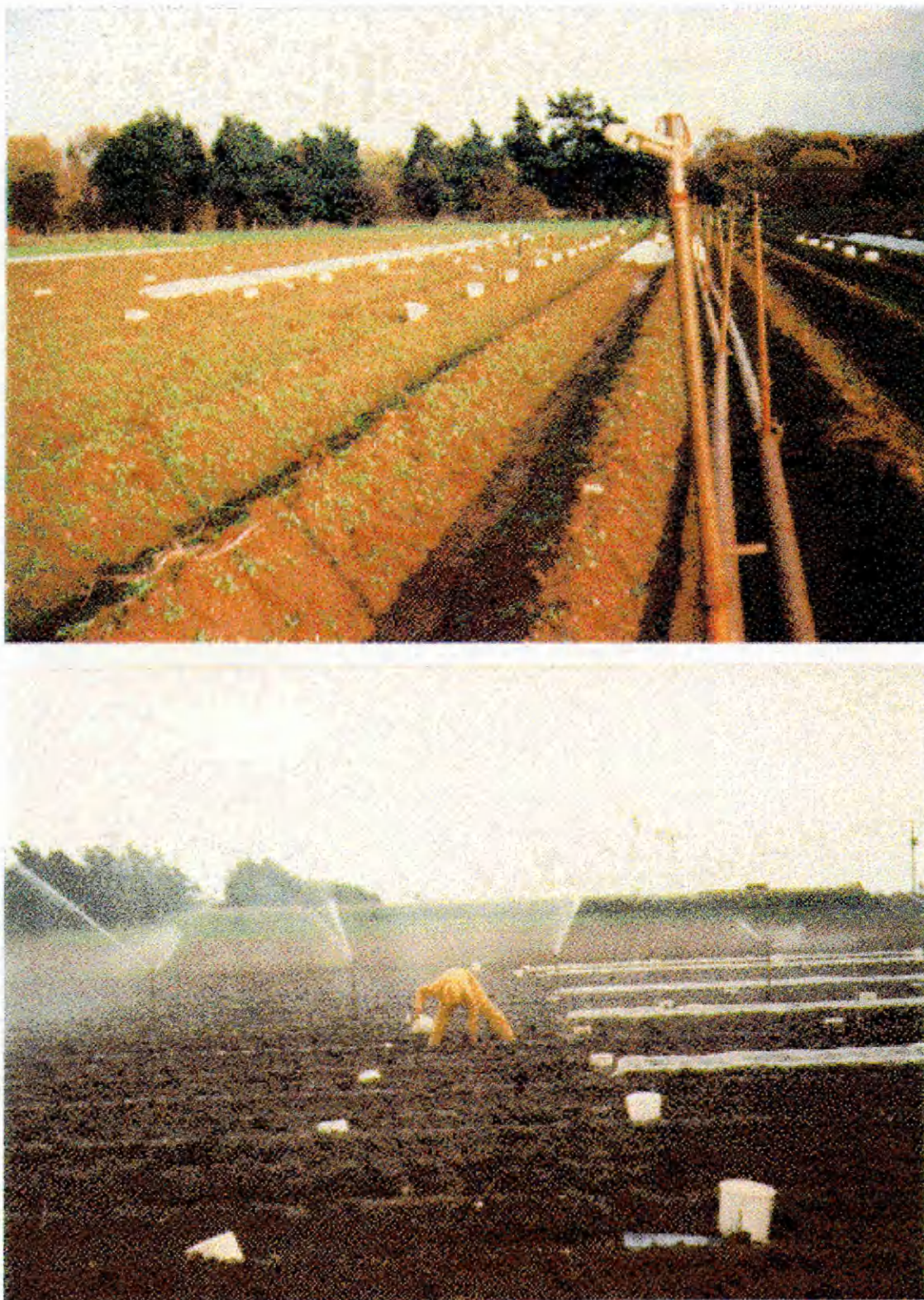


Figure 6.2 Line source sprinkler, lined and unlined furrows and catch-cans in the field

In these experiments the average of water application rate along the line source (experimental furrows) was determined using the records of catch cans. The average of water application pattern across the line source was also found by applying the average of each furrow (plot). The wind speeds and directions were determined with a digital anemometer during the experiments.

6.3.2 Water application pattern along the line source sprinkler

Figure 6.3 shows the water distribution patterns along the line source in the field. Water application rates are not uniform across the line source. Water application rate along the line source is uniform some distance from line source but is less uniform close to line source. This was due to wind distortion (wind speed changed from 1 to 10 m/s) during the different tests or / and blocking the nozzles during the experiments. Table 6.2 summarises the water distribution uniformity of tests together with mean wind speed.

According to Figures 6.3 the water application rates are maximum next to line source sprinkler and then start to reduce across it and become zero at the edge of wetted area. Therefore, the danger of surface runoff and soil erosion are more along the lines close to line source than the distance from it.

6.4 Infiltration

To measure soil infiltration rate a series of tests were carried out in order to find a simple, low cost and practical method for sprinkler irrigation methods. The tests were conducted for three methods, falling head infiltrometer, constant head infiltrometer and rainfall simulator method for a ridge and furrow cultivation practice. Each method was replicated at least for three times.

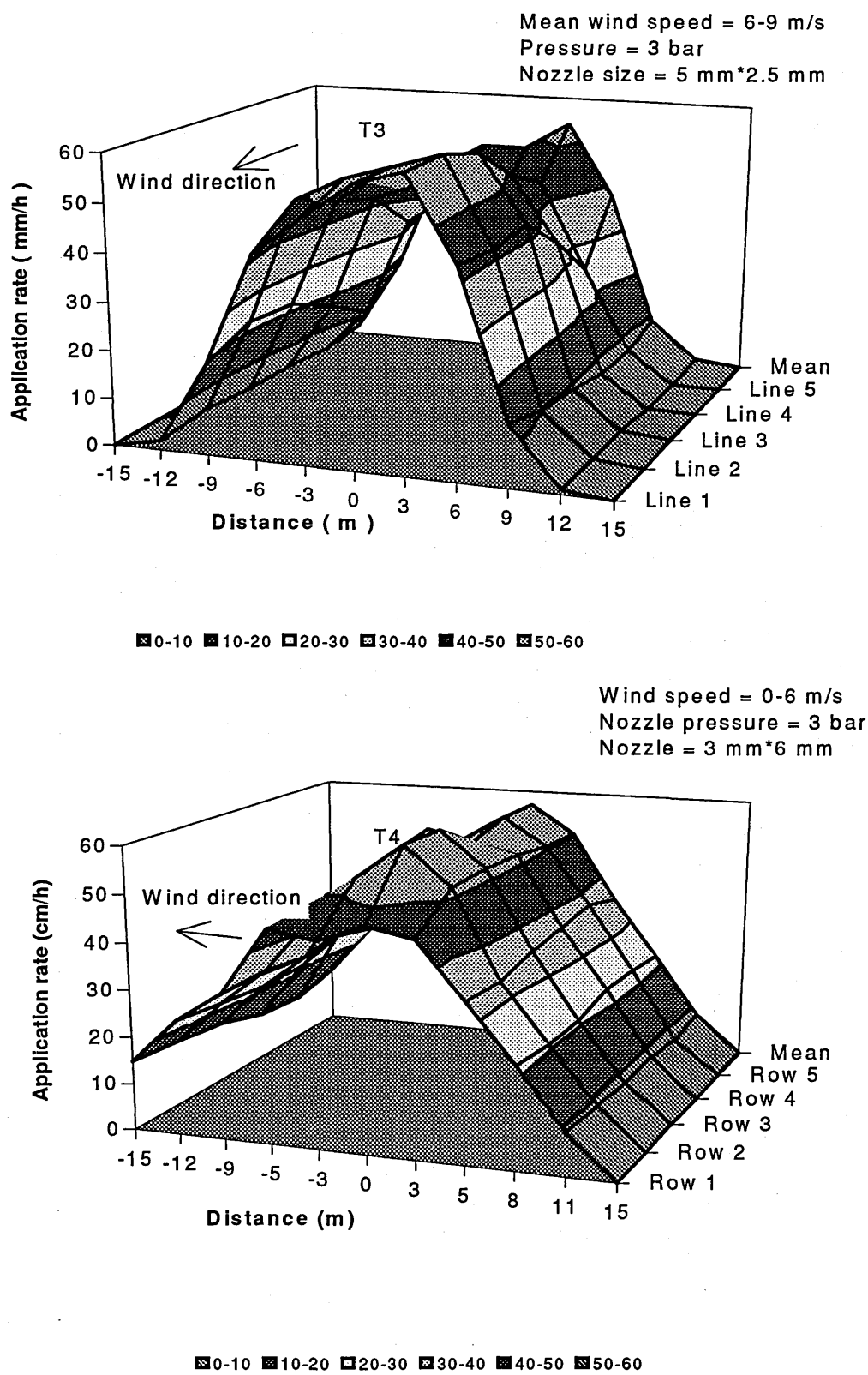


Figure 6.3 Typical water application patterns along the line source sprinkler

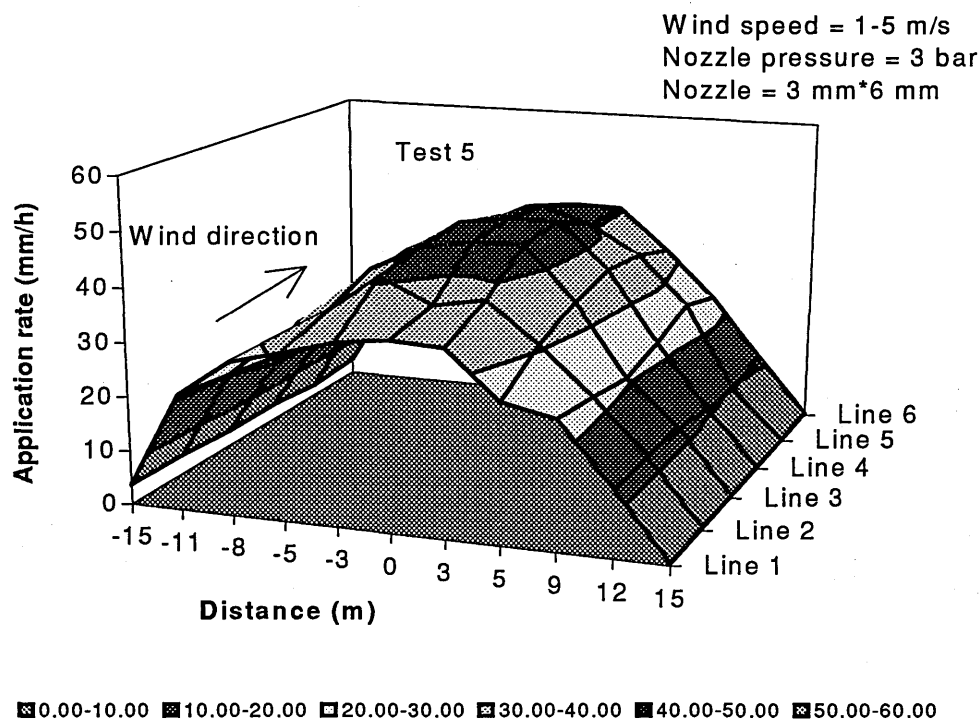
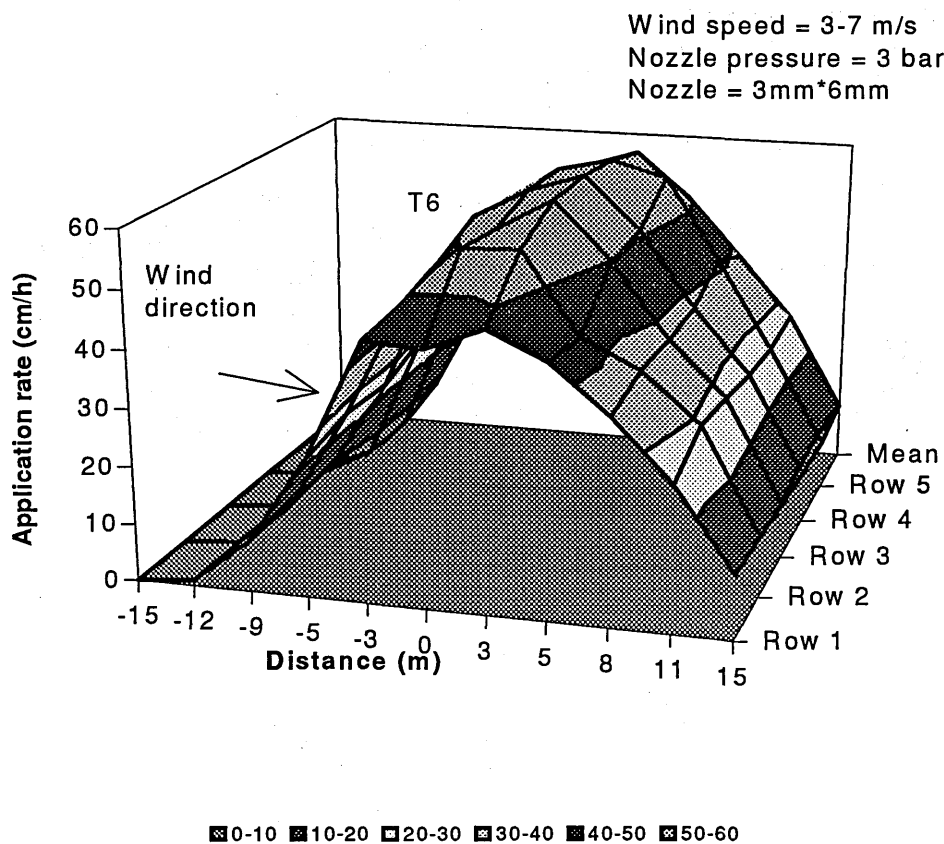


Figure 6.3 Typical water application patterns along the line source sprinkler (contd.)

Table 6.2 Water distribution uniformity of tests for line source (pressure = 3 to 5.25 bar)

Test No	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Mean
Mean wind speed(m/s)	0.5	7	7.5	1	2.5	3	
Distance (m)							
15	88	95	100	100	86	91	93
12	95	92	80	94	92	95	91
8	98	82	81	96	95	88	90
5	98	90	91	96	93	86	92
3	94	89	90	96	92	86	91
0	91	96	85	91	90	93	91
-3	97	93	89	93	91	95	93
-5	94	90	84	97	90	94	91
-9	97	88	95	95	94	78	91
-12	93	89	99	97	91	72	90
-15	83	100	100	94	71	100	91
Mean	93	91	90	95	90	89	92

The time period of experiment was chosen so that the equilibrium condition (when the infiltration rate remains constant with respect to time) was reached. The depth of water was chosen to equal the irrigation water depth, i.e. 150mm. The level of water for constant head furrow infiltrometer was kept constant with respect to time by adding water after each 10 mm drop in water level. In the falling head method, the time for each 10 mm drop in water head was recorded without adding water.

The infiltration rate (i) under sprinkler irrigation conditions in the field was also determined. Water application rate (R) and the surface runoff (Q) were measured in the field for this purpose. The surface runoff was measured with

respect to time. This was carried out as long as the sprinkler system was being operated (from the beginning until the end of irrigation). Then, the water balance equation was used to determine the infiltration rate as follows:

$$R - i - (E + D_i + D_d + e) = Q \quad 6.1$$

Where R = water application rate, Q = runoff rate, i = infiltration rate, D_d = Depression storage, D_i = leaf intercepted storage, E = evaporation and e = experimental error due to device measurement and operator. In this method, it was assumed that the rate of evaporation was approximately zero. Leaf intercepted storage was also zero, because the experiments were carried out on a bare soil. So the equation 6.1 is summarised as follows:

$$i = R - Q - (D_d + e) \quad 6.2$$

The initial infiltration rate for the different methods is different at the early stages of tests (Figure 6.4). This is largest for the constant head furrow infiltrometer and then followed by falling head furrow infiltrometer and rainfall simulator method. This may be because of the head of water which was the highest for constant head method on a recently ploughed soil which was not exposed to rainfall and then followed by falling head and rainfall simulator method on a soil exposed to rainfall. As indicated in Figure 6.4 the infiltration rates on each curve remain constant as infiltration time increases. However, the basic infiltration rates for the falling head and sprinkler methods match together. A comparison of infiltration under sprinkler irrigation and furrow infiltrometer methods is made in Table 6.3.

Averaged infiltration rate under sprinkler irrigation changes with the area of experimental plot. For instance, the infiltration flow curves along the furrow 5 test no 6 and test no 7 are shown at three measuring points in (Figure 6.5).

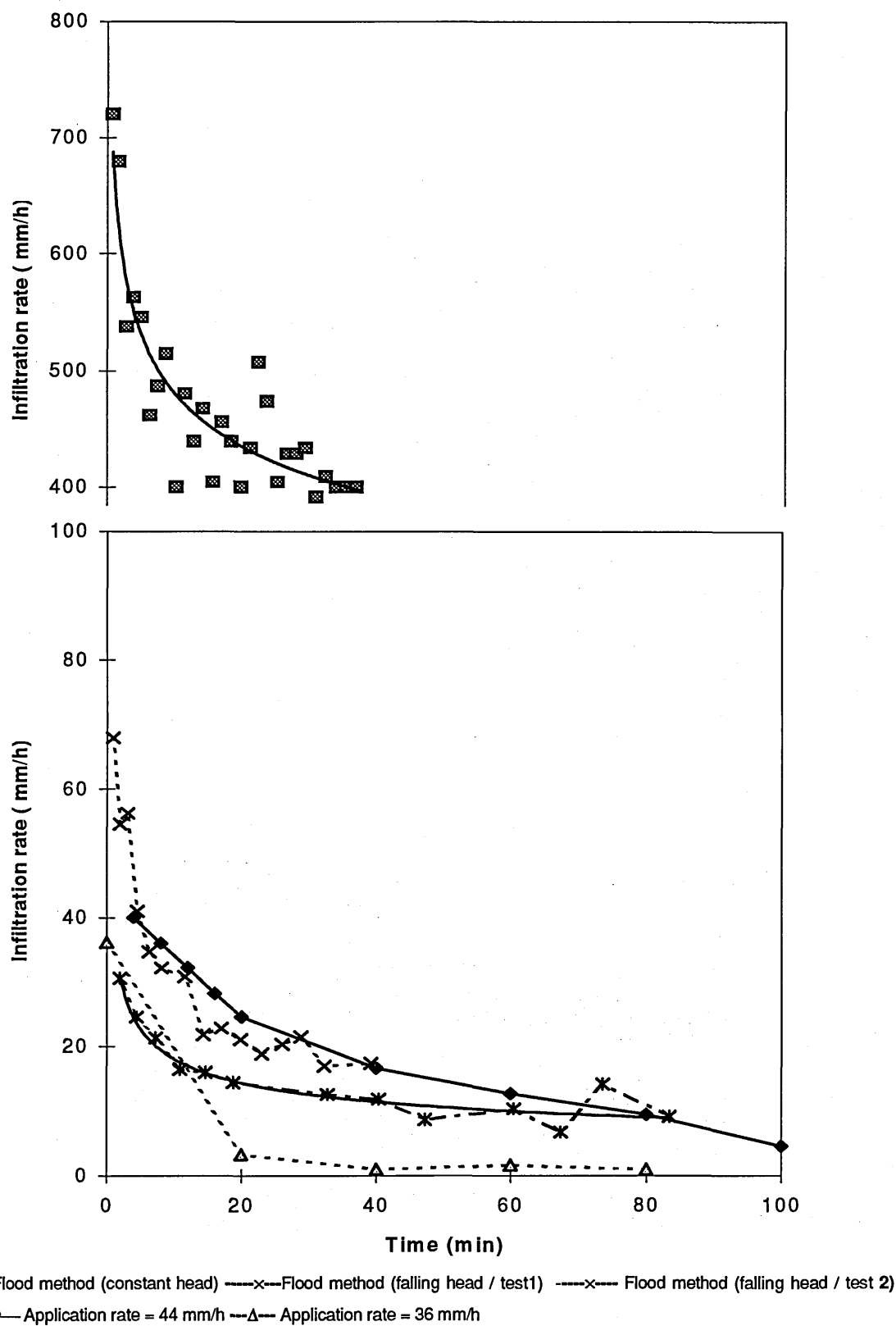


Figure 6.4 Typical example of infiltration rates under sprinkler irrigation and flood method

The upper curve indicates the infiltration at the end of furrows, the middle one relates to the section two (from 45% of plot) and lower one belongs to upper measuring section (from 27% of plot). This means that the larger the catchment length the bigger the average infiltration.

Overall, the falling head infiltrometer may be recommended for measuring the basic infiltration rate for sprinkler irrigation. Using this method can also save time and money. However, from the information in Table 6.3 the final infiltration values ($\approx$ saturated hydraulic conductivity) are used for KINEROS-EUROSEM model validation and infiltration equations are used for runoff prediction in the field by the OLF model (see Figure A.1 in Appendix A.1)

Table 6.3 Comparison of infiltration under sprinkler irrigation and furrow infiltrometer methods.

Methods	Furrow/Test	Application rate	Equation	Regression Coefficient	Final infiltration rate
		mm/h			mm/hr
Rainfall simulator:					
	Furrow2/Test5	15	$y = 22.255x^{-0.1256}$	0.8184	12.3
	Furrow3/Test5	26	$y = 22.947x^{-0.178}$	0.667	13.0
	Furrow9/Test5	30	$y = 34.211x^{-0.403}$	0.562	6.4
	Furrow5/Test5	38	$y = 37.746x^{-0.016}$	0.752	8.6
	Furrow7/Test5	41	$y = 46.494x^{-0.277}$	0.996	13.4
	Furrow5/Test6	44	$y = 129.85x^{-0.6101}$	0.872	4
Mean					9.7
Furrow infiltrometer:					
	Constant head		$y = 669.51x^{-0.1444}$	0.796	400
	Falling head (test 1)		$y = 72.581x^{-0.3984}$	0.96	17
	Falling head (test 2)		$y = 8.568x^{-0.3303}$	0.834	8
	Mean (test 1) and (test 2)				12.5

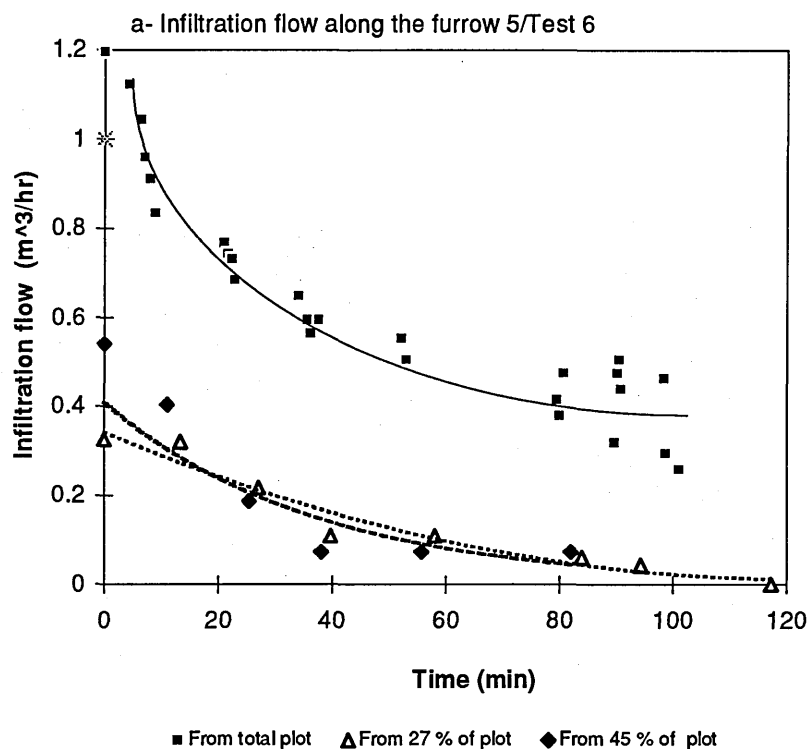
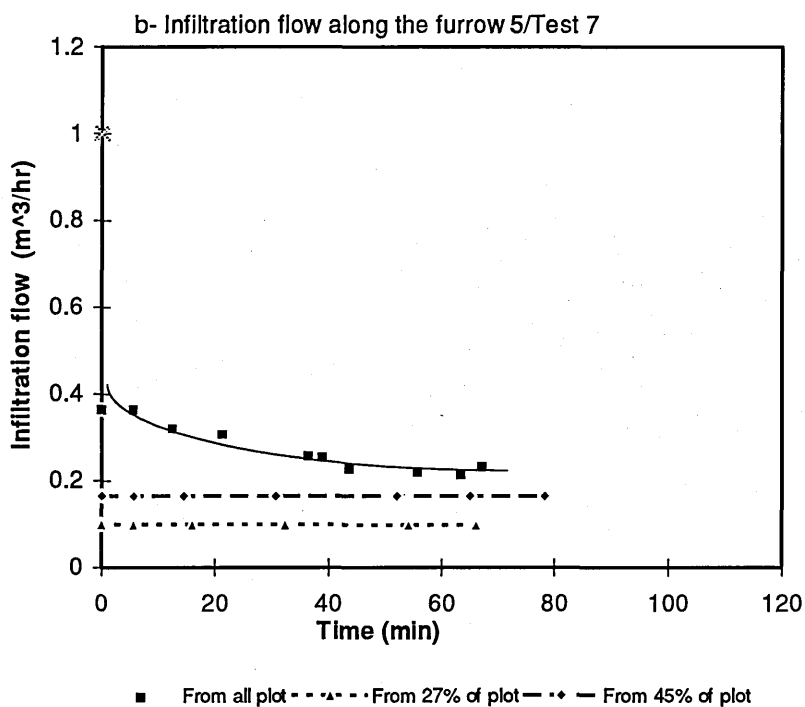


Figure 6.5 Typical example of variation of infiltration flow along unlined furrows

6.5 Surface runoff

When the application rate exceeds the infiltration capacity, surface runoff starts and the discharge increases down the slope. Downstream increases in runoff flow are the result of continuous inflow of water from overland flow and direct catchment rainfall (or water application). If the water application rate (R) is less than the infiltration capacity (i) no runoff will occur and infiltration rate equals the rainfall intensity. Runoff velocity depends on slope angle and roughness, but also relates to the type of flow (laminar or turbulent).

Both lined and unlined furrows were tested. Lined furrows were used to understand the model operation and find the errors that might be exist in collecting the data in the field condition. The unlined furrows were used to collect runoff data for model evaluation in the field condition.

6.5.1 Surface runoff measurement

Surface runoff at the end of furrows was measured using the volumetric method and also WSC flume (Figure 6.6). This was done under the shower of water when the system was running. The rate of runoff (mm/hr) from each experimental plot was determined by dividing the runoff discharge to the area of the micro-catchment (ridge and furrow area) and the water application time. The water depth along some of the unlined furrows was measured at three points by using a vernier gauge. These data were used to find the Manning roughness coefficient in the furrows for soil (see section 5.4).

Six tests were carried out for a variety of rainfall runoff conditions. These conditions included system pressure, water application time, discharge and two different furrow lengths, 12.3 and 24.3m (Appendix D.1).



Figure 6.6 Discharge measuring devices in the field

6.5.2 Runoff from Lined furrows

The runoff rates along the lined furrows were measured with respect to time. Figure 6.7 shows the typical example of runoff hydrographs from lined furrows (Furrows 4, 6, 8 and 10 (see Table 6.4)). It is expected that the second stage of runoff hydrographs match the water application rates, because there was no infiltration. However, this would not occur until depression storage was filled. Even after filling the ditches there is still some difference between water application rates and the runoff hydrographs. The shape of hydrographs are rather different. This is because the depression storage in the lined furrows is different and the water application rate was not perfectly uniform. In addition to these there are errors arising due to the experimental device and operator.. Figure 6.8 also shows the runoff coefficient curves with time. According to this figure the runoff coefficients at the early stage of rainfall are less than one but rise close to one when equilibrium conditions are reached. This means inflow and outflow rates to plots were nearly equal at this stage. The average of runoff coefficients for the steady part of the runoff hydrographs resulted from lined furrows is tabulated in Table 6.4. From this table it may be concluded that when the water application rate is smaller the deviation of runoff coefficient from one is larger. So it is recommended not to use runoff data from low water application rates for model evaluation. From Figure 6.7 can be found that the time to start runoff is larger when the water application rate is smaller. This is because the depression storage takes longer to fill when the water application rate is low.

6.5.3 Depression storage

Depression storage is the soil surface storage which should be filled by applied water before runoff takes place. The value of depression storage is determined using the period in which no runoff occurs. So the value of

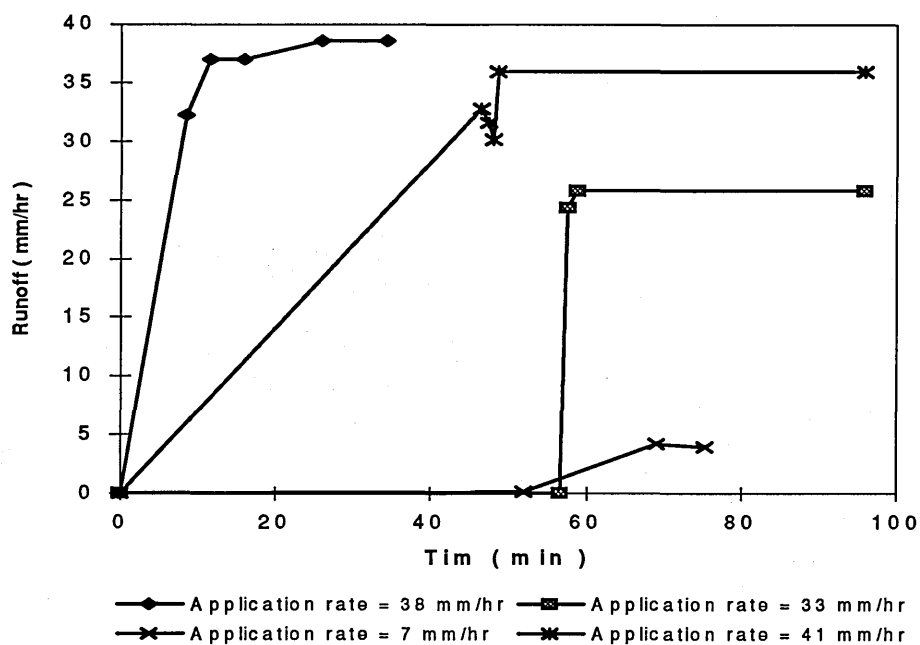


Figure 6.7 Runoff hydrographs from lined furrows at different water application rates.

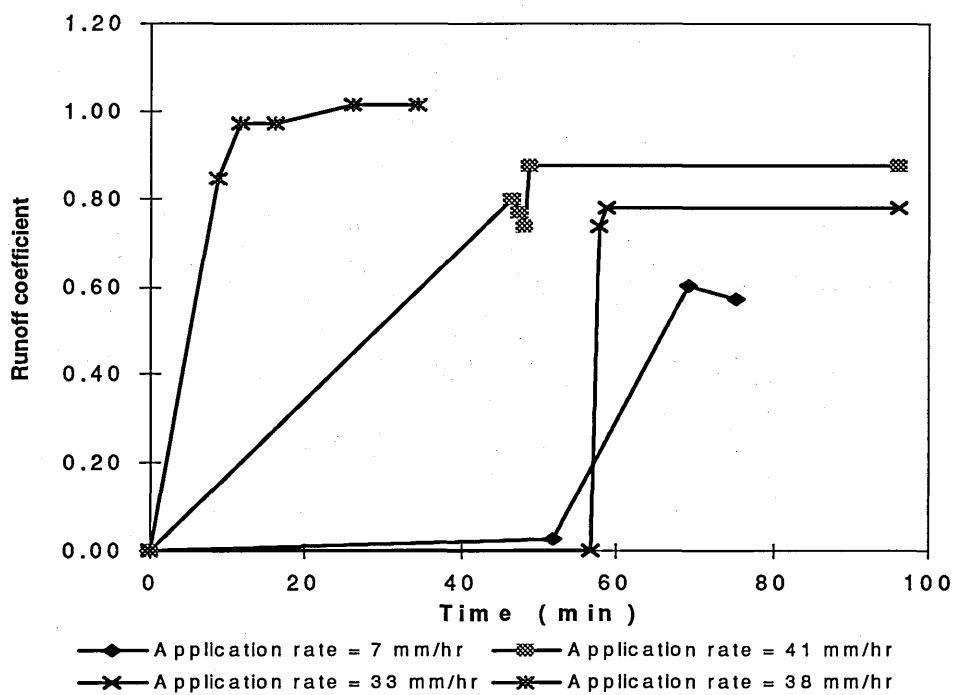


Figure 6.8 Runoff coefficients for lined furrows

Table 6.4 Runoff coefficient, depression storage and error in lined furrows

Test	Furrow	Application rate	Mean runoff coefficient	Depression storage	Error
		mm/hr	%	mm	mm/hr
1	4	26	1.09	1.04	-2.26
1	6	46	0.93	1.9	0.44
1	8	38	1	3.1	0.5
Mean			1	2	-0.44
2	6	49	1.06	1.85	1.6
2	8	48	1.08	2.13	-1.9
Mean			1.07	2	-0.15
3	6	48	0.64	-----	2.5
3	8	50	0.78	-----	-----
3	10	7	0.59	3.03	2.9
Mean			0.67	3.03	2.7
5	4	33	0.77		
5	6	41	0.81	2.5	5.1
5	8	38	0.86	2.2	4.6
Mean			0.81	2.3	4.85

depression storage will be the product of water application rate and time to start runoff. Theoretically when runoff starts the rising limb of hydrograph should sharply rise and reach the steady state. However, in practice this will not occur because of the changeable conditions in the field (Figure 6.7).

The depression storage values are tabulated in Table 6.4. These values are small and seem to be reasonable whenever the runoff data were collected per short time intervals. The mean of these values can be accepted as a soil surface depression magnitude. The mean values range from 2 to 3 mm. The

big figures which are out of this range are not included in Table 6.4. Obviously, the values of depression depth for unlined furrows is smaller than that of lined furrows. This is because, the impact of applied water during the successive irrigation events that breaks the clods and reduces the depression storage on the soil surface.

6.5.4 Systematic errors in observed data

Errors in measurement were determined using the steady part of runoff hydrographs of lined furrows. These are presented in Table 6.4. The values that may be positive or negative are in a small range. So, to obtain the real values of water application rate for unlined furrows the mean value of errors (if it is significant) must be added to the observed water application rate in each test. The mean error values range from -2.3 to 5 mm/hr.

6.5.5 Runoff from unlined furrows

Figure 6.9 shows the typical examples of observed runoff hydrographs together with application and infiltration curves along the unlined furrow. According to these figures runoff and infiltration processes continue, even when water application is stopped. Infiltration continues not over whole, but from a fraction of the catchment which is covered with water until the soil surface is completely depleted. In fact, water flow into soil reduces as the area covered with water declines (See section 2.5.6). After ceasing irrigation, runoff rates also reduce and after a while stop. This volume of runoff under the falling limb of hydrograph depends on water application rate and soil surface topography. The higher the application rate, the more the runoff volume. This volume can be used to find the Manning roughness coefficient (Mohamoud 1992). The fluctuations in runoff hydrographs are due to variation in water

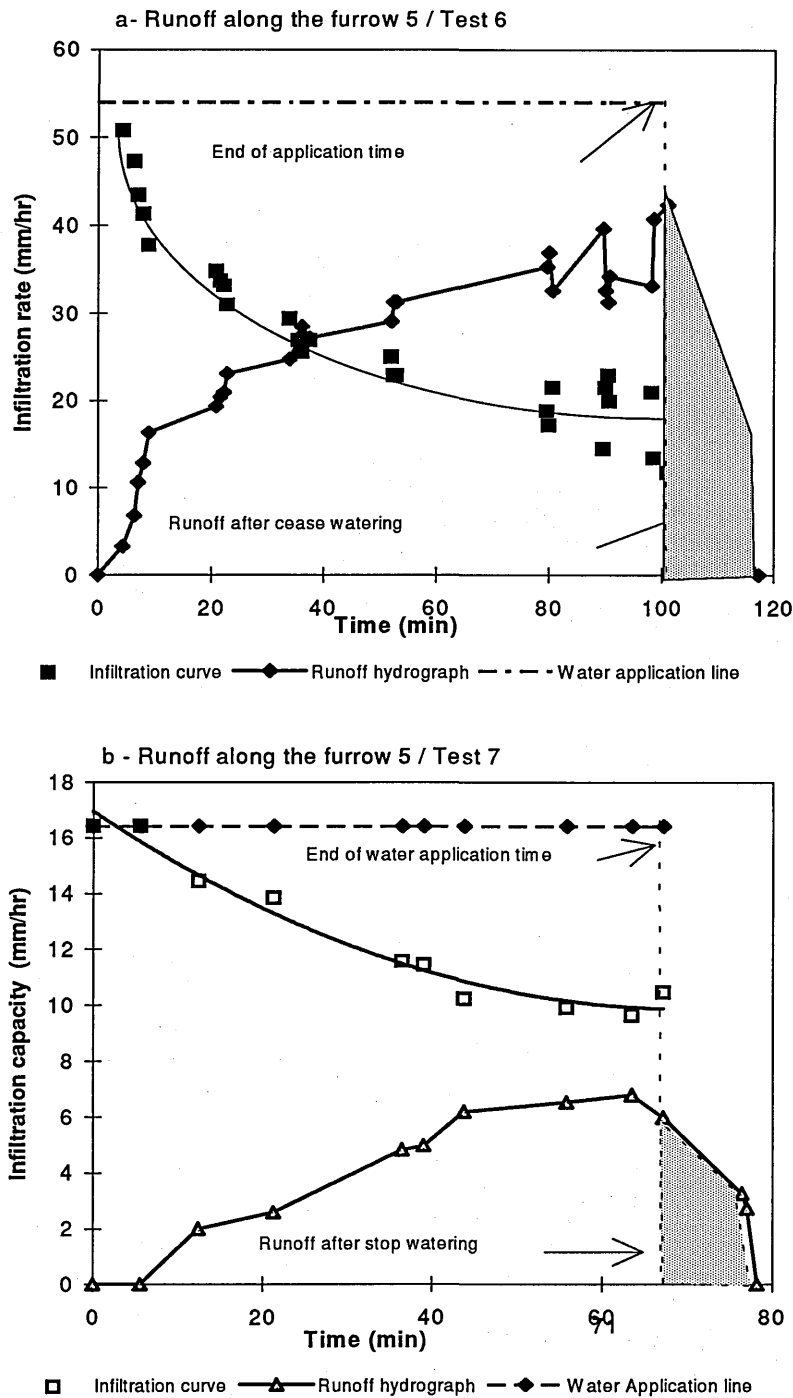


Figure 6.9 Typical example of observed runoff hydrographs together with application lines and infiltration curves.

application rates caused by wind speed. The higher the instantaneous wind velocity the higher these variations. Two typical examples of the effect of water application rate on runoff are indicated in Figures 6.10 for two tests, test 3 and test 5 in the field. In test 3 when the water application rate is increased from 36 to 46mm/h the peak runoff rate changes from 14 to 27mm/h. The same phenomenon occurs when water application rate is increased from 15 to 41mm/h. So not only the peak flow rate but also time to peak, time to runoff, volume of runoff and ultimately the shape of hydrograph are highly affected by the rate of water application rate.

6.5.6 Runoff coefficient

According to Figure 6.11 the runoff coefficient changes with time. This is because the soil condition was changing during the irrigation. This graph also shows that at the beginning of sprinkler irrigation runoff is zero and after a while runoff starts. Theoretically, if the irrigation persists for a long time the runoff coefficient remains constant. This case happens when the soil is in an equilibrium condition.

Figure 6.12 shows the variation of runoff coefficient during each irrigation compared with previous irrigations for a sandy loam soil. According to this graph the runoff coefficient for the irrigation number five (Test 5) is more than that of the third irrigation (Test 3) and this is more than that of the second irrigation (Test 2). Therefore, runoff coefficient not only changes with time during each irrigation event, but also changes with the number of previous irrigations. This is because the water application rate and the impact of droplets which cause crusting and sealing of the soil surface. The more the number of previous irrigations, the greater is the runoff coefficient. In theory the water application rate for each irrigation following the previous one should decline in order to reduce or prevent runoff. Even the water application rate at the mean time of irrigation should be less than that of at the beginning of each

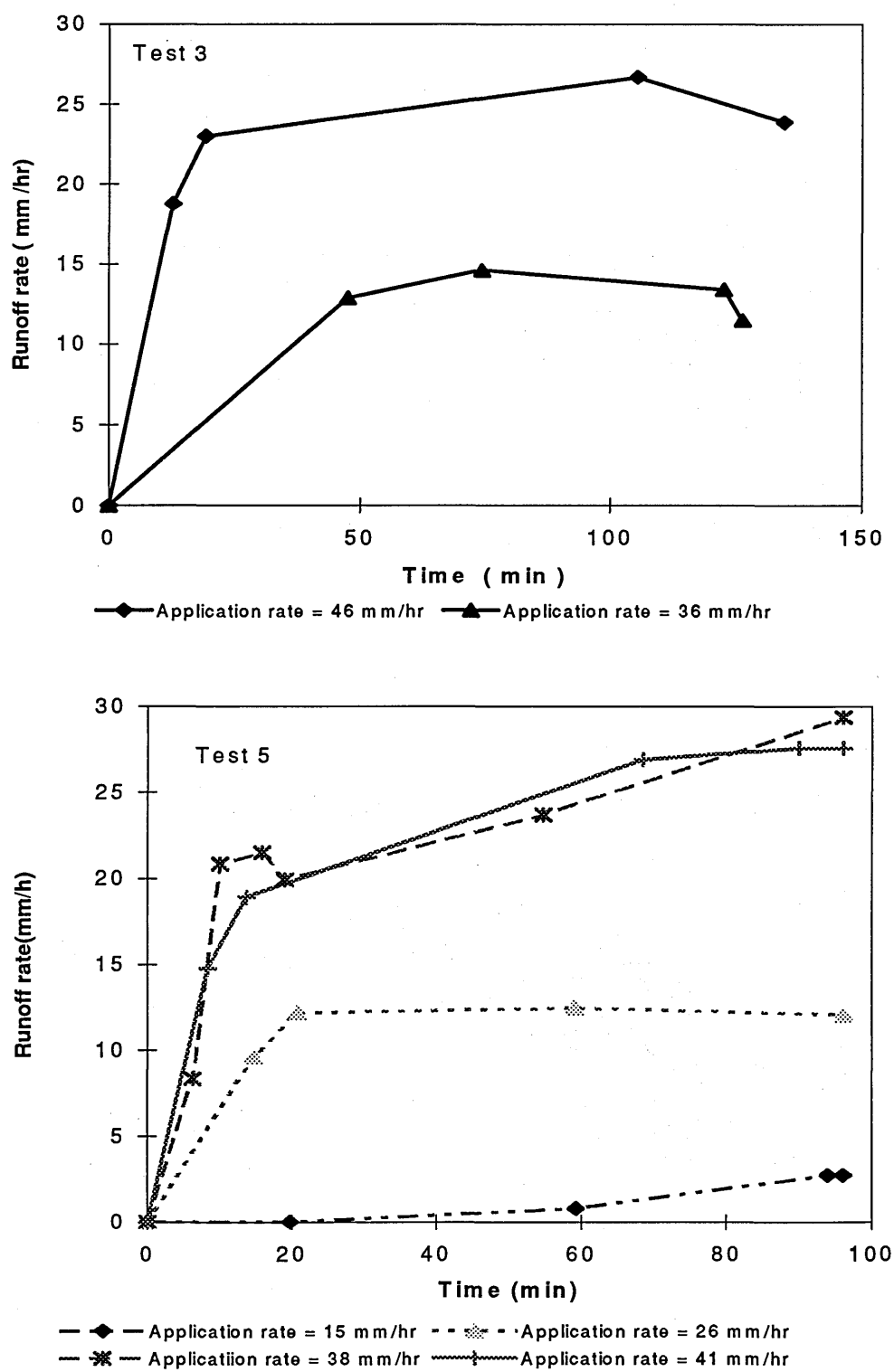


Figure 6.10 Effect of water application rate on runoff hydrograph in the field.

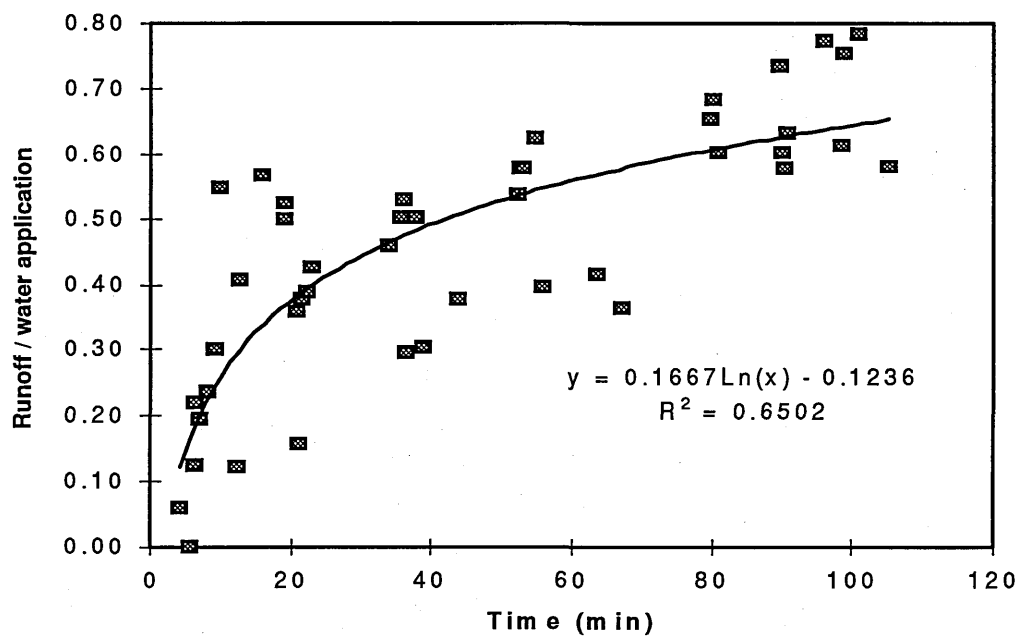


Figure 6.11 Variation of runoff coefficient with time during each irrigation

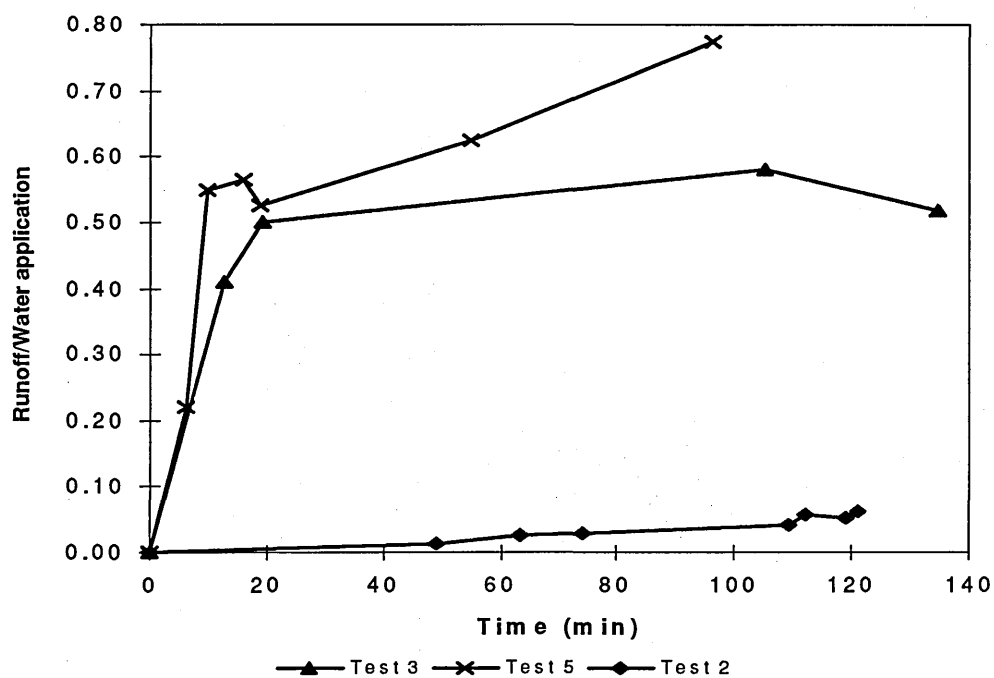


Figure 6.12 Variation of runoff coefficient during each irrigation and with the number of previous irrigation

irrigation event to reduce runoff. However, there are many difficulties to achieving this which make it impractical.

6.6 Comparison between observed and predicted hydrographs

The comparison between observed and predicted runoff hydrographs is made graphically and statistically in this section. The comparison is presented individually for each test and general comments are also presented here. Further statistical and graphical analysis are undertaken for hydrograph parameters as well.

6.6.1 Individual tests

Observed runoff hydrographs were made by plotting the measured data in the field against time. Predicted runoff hydrographs were obtained by putting the appropriate field parameters in the model and running it. These are compared graphically in Figure 6.13. As can be seen from Figure 6.13 (a) both observed and predicted runoff hydrographs start a little time after rainfall. This is because the soil water content of Furrow 9 /Test 3 was relatively high at the beginning of test. When the surface runoff starts the runoff hydrograph rises. However, the rising limb of hydrograph is not very sharp, because the water application rate is low and the hydraulic conductivity is high. Runoff rate reaches to a peak flow rate after a while (time to peak). This is the point where the second stage of runoff hydrograph starts and then remains constant. The beginning of second stage and peak flow rates of both hydrograph are more or less same. The peak flow rate of both hydrographs remains constant for a time period. During this period runoff is in an equilibrium condition; this means that the saturated hydraulic conductivity has been reached so that the runoff rate remains constant until the end of water application period. When water application stops the falling limb drops steeper than the rising limb of hydrograph. This indicates that runoff rate reduction is more than that for rising

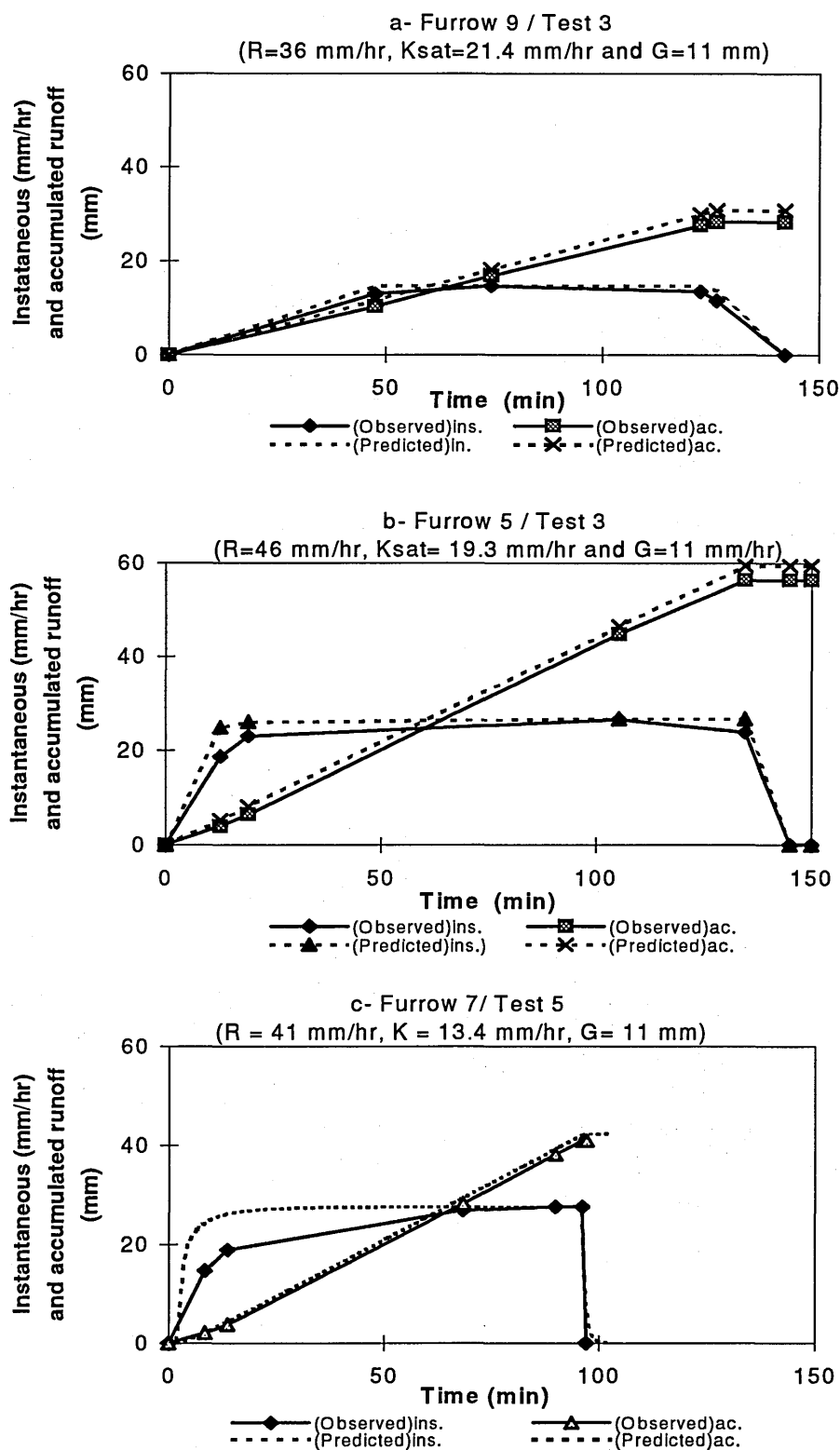


Figure 6.13 Comparison between observed and predicted runoff for unlined furrows in the field.

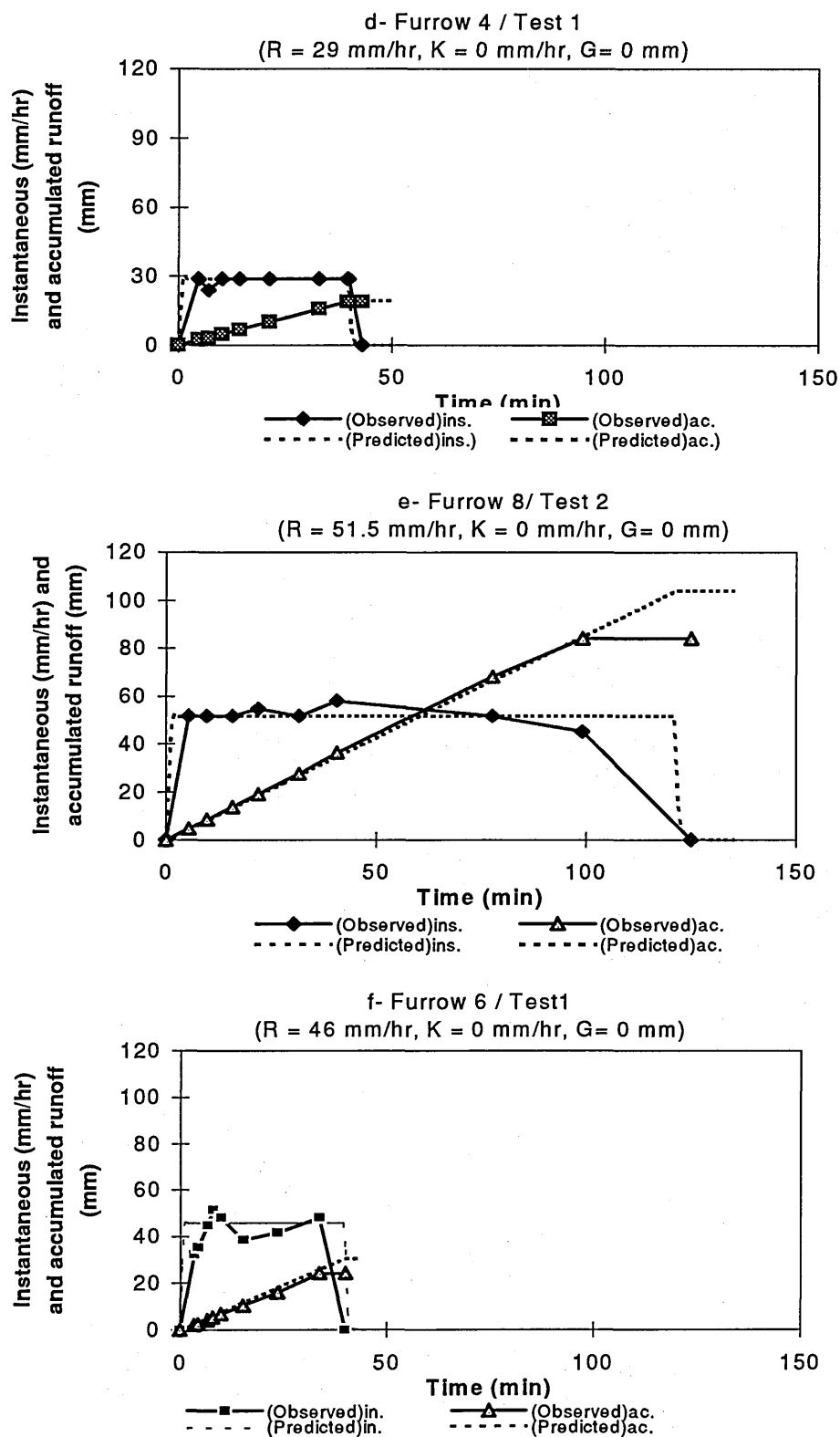


Figure 6.13 Comparison between observed and predicted runoff for lined furrows in the field (contd.)

limb associated with water application. This is because the depth of runoff was low at the beginning of irrigation and has increased to its highest level at end of the rainfall. This caused rapid depletion of water from the soil surface.

From Figure 6.13 can be seen that the observed and predicted accumulated hydrographs increase simultaneously with nearly the same slope. When the rainfall stops, the slope of both hydrographs suddenly declines and continues until the end of runoff. The total runoff and runoff duration can be determined using the accumulated runoff hydrograph. The runoff duration is the period time in which runoff process occurs. This is also well simulated by the model. The interpretation of chart (a) can also be applied to Furrow 5 / Test 3 and Furrow 7 / Test 5 (Figures (b) and (c)). However, the slope of the rising limbs of these two hydrographs is steeper, due to the higher water application rate and lower hydraulic conductivity. The slope of the falling limbs is steeper than that of chart (a). This may be due to the greater depth of water on the soil surface immediately after rainfall that caused rapid depletion of runoff from the soil surface.

A comparison is made also between observed and predicted runoff hydrographs from lined furrows (Figure 6.13 - d, e and f). It can be seen that both observed and predicted runoff start early from the beginning of rainfall. This is because the experimental plots are impervious and no losses occurred through infiltration. However, the rising limb of the predicted hydrographs rises suddenly and that of the observed hydrograph increases gradually. This may be due to the lack of data during the period of observed time to peak or non-sensitivity of model to small values of roughness ratio along the slope (topographic not Manning's roughness, see section 5.2.5). So the predicted time to peak is shorter than the observed time to peak. However, the predicted and observed peak flow rates are the same until the end of the irrigation. When rainfall stops the falling limbs of both hydrographs drop, but that of the observed hydrograph is again slower than that of the predicted hydrograph.

This may be due to the lack of recorded data in this period. The time to end runoff is the same for both hydrographs.

The interpretation of chart (d) can also be applied to charts (e) and (f). Regarding the second stage of observed hydrograph in chart (f), the fluctuation is due to the wind speed that affected water application rates and ultimately the runoff rates.

6.6.2 General comments

Figure 6.13 (a, b and c) show that the model slightly overestimates the runoff rates within the irrigation periods, but these are not significantly different. This is because instantaneous and accumulated observed and predicted hydrographs match together successfully.

It can be seen that the total runoff increases as the water application rate and / or water application time increases; and / or hydraulic conductivity reduces. For example, the slope of the accumulated hydrograph in test (b) is more than that in test (a). This is because the water application rate ($R = 46\text{mm/h}$) and hydraulic conductivity ($K = 19.3\text{mm/h}$) in test (b) are respectively more and less than those ($R = 36$ and $K = 21.4\text{mm/h}$) in test (a). This conclusion can also be drawn from figure (b) and (c). The hydraulic conductivity of test (b) and its water application rate are higher than those for test (c). These two parameters have equal weight and affect runoff in opposite direction and so neutralise each other. This is why the slopes of accumulated lines of Test (b) and (c) are equal. These indicate that the dominant factors in runoff creation are water application rate and hydraulic conductivity. Overall, the slope of each accumulated runoff is an indicator of rainfall and soil characteristics.

A comparison between observed and predicted runoff hydrographs for lined furrows in the field are also made in Figure 6.13. From this comparison can be found that the observed runoff rates are slightly underestimated during the water application time. According to charts (d, e and f) the slope of accumulated hydrographs of chart (e) is greater than that of chart (f) and that of chart (f) is greater than chart (d). This is because of the greater application rate of chart (e) and (f) compare to chart (d).

The second stage of predicted runoff hydrographs for lined furrows shows an equilibrium condition in which the rates of runoff are approximately equal to the water application rates in three hydrograph comparisons. This is true, because there is no water penetration into the soil when the furrow surface is lined with polythene. Therefore, the soil parameters such as hydraulic conductivity, capillary drive and soil water content are zero. Consequently, water loss through infiltration is zero and runoff rates at equilibrium condition are equal to water application rate. In fact the equilibrium condition should occur when the depression storage is perfectly satisfied with falling water.

Regarding the observed runoff hydrographs for lined furrows the second part of the hydrographs is not perfectly in an equilibrium situation and the rates of runoff are not accurately equal to the water application rate. There are some fluctuations in hydrograph as well. These are mainly due to wind problem during the experiments. However, the majority of data points on the observed runoff hydrographs (a) and (b) have the same values as predicted runoff. Accordingly, these values can be an identification of real inputs (i.e. water application rates) to the related experimental plots (furrow 6 and furrow 4). So if a correction of 2mm/h is applied to water application rates of these two plots (see 6.5.4) the input and output values will match together.

The observed and predicted hydrograph parameters are presented in Table 6.5. From these values can be understood that there is not much difference

Table 6.5 Comparison between observed and predicted hydrograph parameters in the field

Plot No/ Test No	Type	Time to runoff (Tr)	Time to peak (Tp)	Peak flow rate (Qp)	Time to end (Te)	Total runoff (Qv)
Unlined furrows:		(min)	(min)	(mm/hr)	(min)	(mm)
Furrow 9 / Test 3	Observed	0	74.4	14.6	142.1	28.2
	Predicted.	2.5	72	14.8	142.1	31
Furrow 5 / Test 3	Observed	0	105.3	26.7	145	56.3
	Predicted.	2.5	112.5	26.7	141.5	57.3
Furrow 7 / Test 5	Observed	0	90	27.6	97	41
	Predicted.	0.2	96	27.6	102	42.3
Lined furrows:						
Furrow 6 / Test 1	Observed	0	8.0	51.5	40	24.1
	Predicted.	0	13.5	46	44	30.5
Furrow 8 / Test 2	Observed	0	5.3	51.5	125	84
	Predicted.	0	13.5	51.5	128.5	104
Furrow 4 / Test 1	Observed	0	4.8	28.9	43	19
	Predicted.	0	13.5	29	44	19.3

between two groups of parameters related to either lined or unlined furrows. However, further statistical analysis is required to judge how significant the discrepancy between observed and predicted hydrograph parameters is?

6.6.3 Statistical analysis of runoff hydrographs

A statistical comparison between predicted and observed runoff hydrographs is made in Table 6.6. In this table different indices have been used for this purpose. Model efficiency and regression coefficient are two of these approaches whose values are close to one (ideal slope for regression line) for all trials, except Furrow 6 / Test 1. The regression coefficients of four tests are more than 97 percent. This means 97 percent of total variations in

Table 6.6 A summary of statistical analysis of model validation in the field

Test	$\Sigma(\text{predicted- observed})^2$	$\Sigma(\text{Observed- mean observed})^2$	Efficiency	Root square error	mean Equation	Observation	Correlation coefficient (R^2)	Standard Error
Lined furrows	F1	F2	E	RMSE			Calculated Tabulated	
Furrow 9/ Test 3	8.6	233.7	0.963	1.20	$y = 1.0792x + 0.138$	6	0.989 0.811	0.867
Furrow 5/ Test 3	53.3	2984.1	0.982	2.98	$y = 1.0911x + 0.579$	6	0.974 0.811	2.428
Furrow 7/ Test 5	208.7	938.0	0.777	5.11	$y = 0.9391x + 4.072$	8	0.892 0.707	4.520
Unlined furrows								
Furrow 6 / Test 1	2467.3	5460.7	0.548	15.00	$y = 0.6646x + 17.033$	11	0.547 0.602	13.190
Furrow 8 / Test 2	93.7	5966.4	0.984	2.92	$y = 0.9737x + 0.7561$	11	0.985 0.602	3.140
Furrow 4 / Test 1	49.5	1773.2	0.972	2.12	$y = 0.9767x + 0.3377$	11	0.972 0.602	2.320
Slope								
Intercept								
	a	Lower 95%	Upper 95%	b	Lower 95%	Upper 95%		
Lined furrows								
Furrow 9/ Test 3	1.079	0.922	1.236	0.138	-1.552	1.828		
Furrow 5/ Test 3	1.091	0.844	1.338	0.579	-4.118	5.276		
Furrow 7/ Test 5	0.939	0.612	1.266	4.072	-2.070	10.214		
Unlined furrows								
Furrow 6/ Test 1	0.665	0.209	1.121	17.033	0.282	33.783		
Furrow 8/ Test 2	0.974	0.882	1.066	0.756	-3.327	4.839		
Furrow 4/ Test 1	0.977	0.852	1.101	0.338	-2.677	3.352		

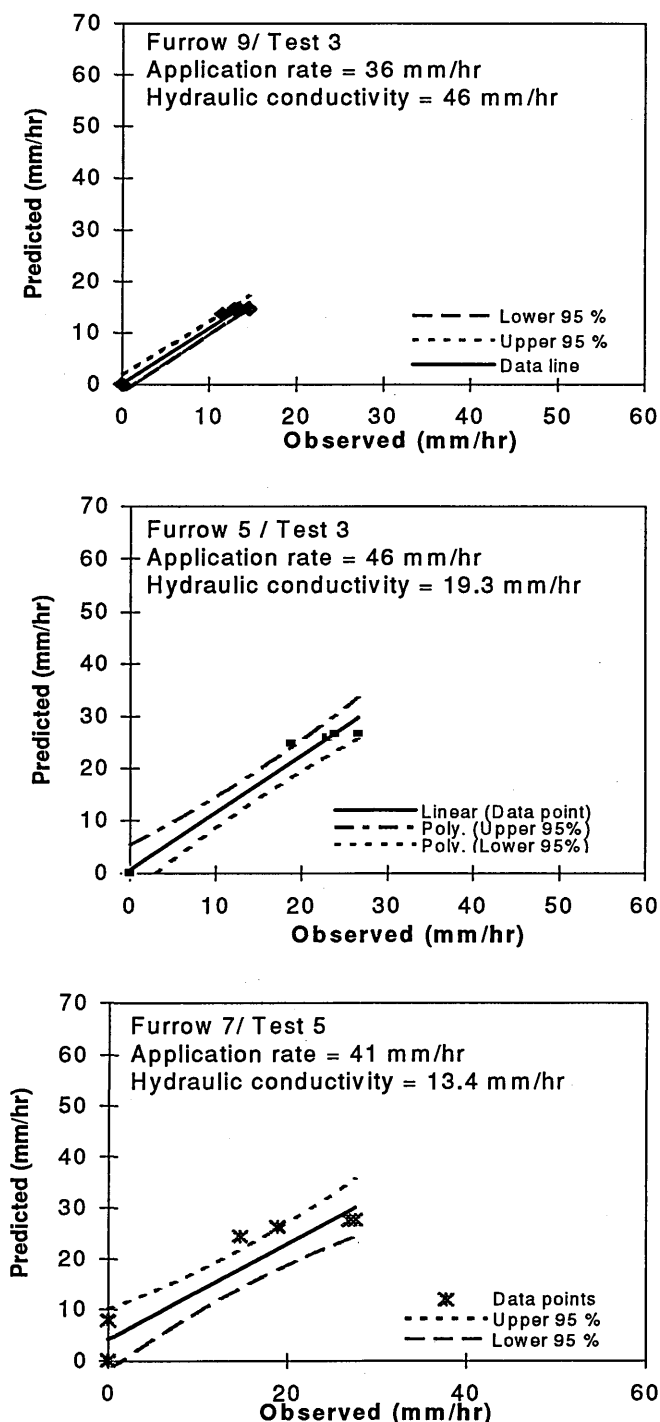


Figure 6.14 Correlation between predicted and observed runoff data together with confidence bands for unlined furrows

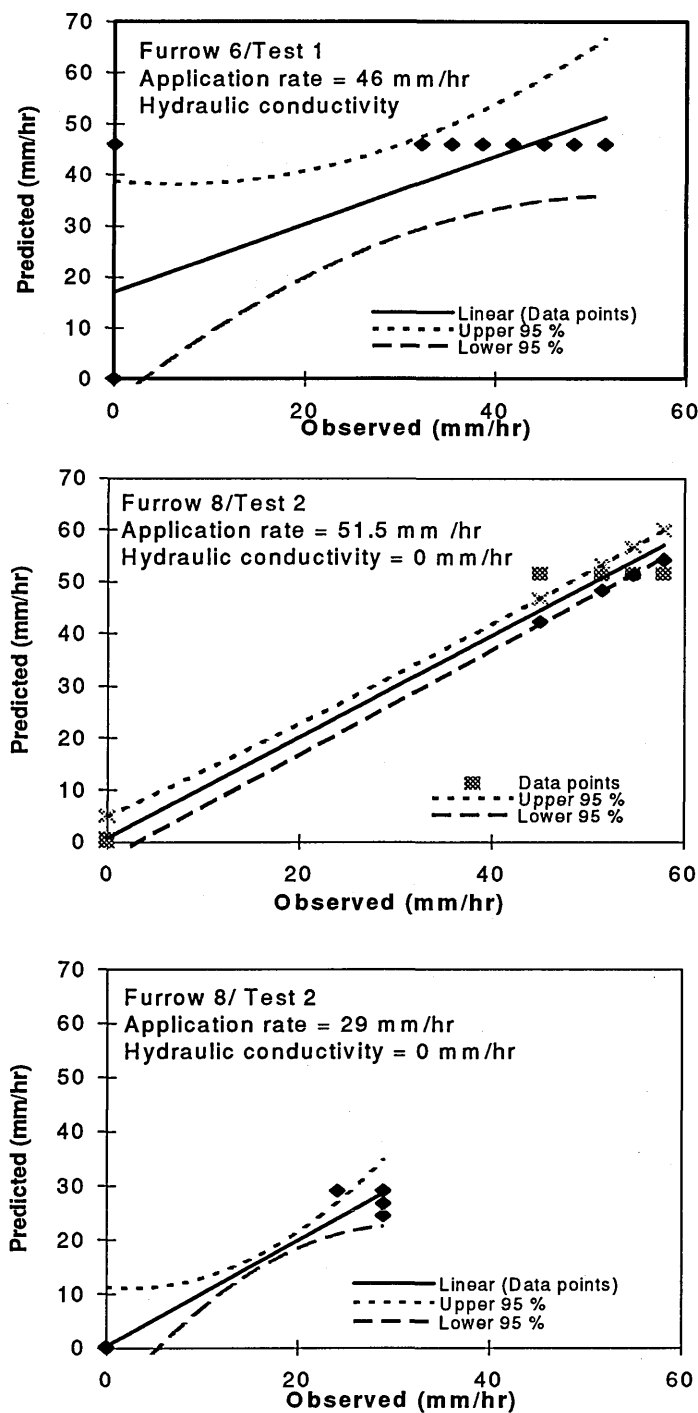


Figure 6.14 Correlation between predicted and observed runoff data together with confidence bands for lined furrows (contd.)

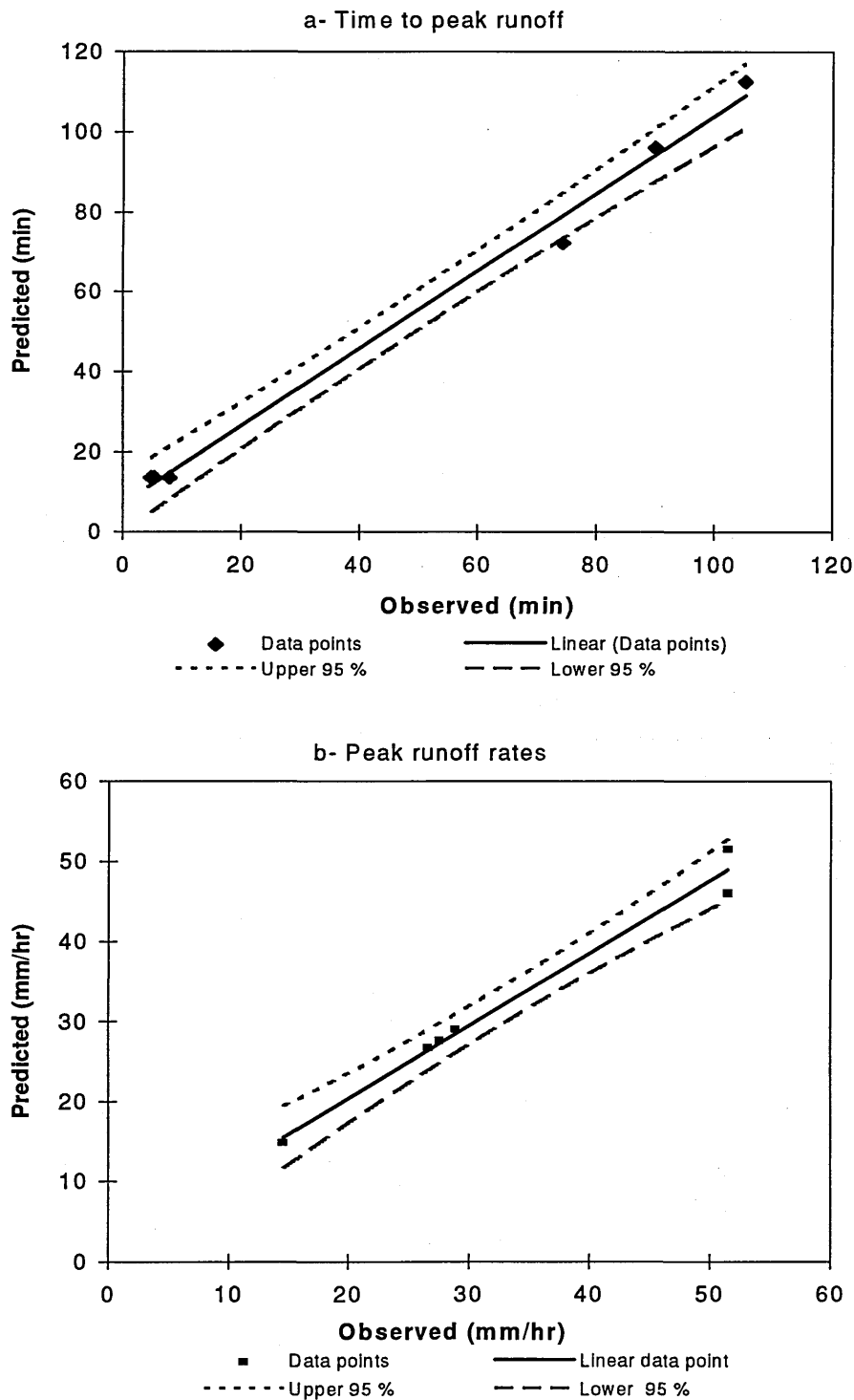


Figure 6.15 Correlation between observed and predicted hydrograph parameters together with confidence limits

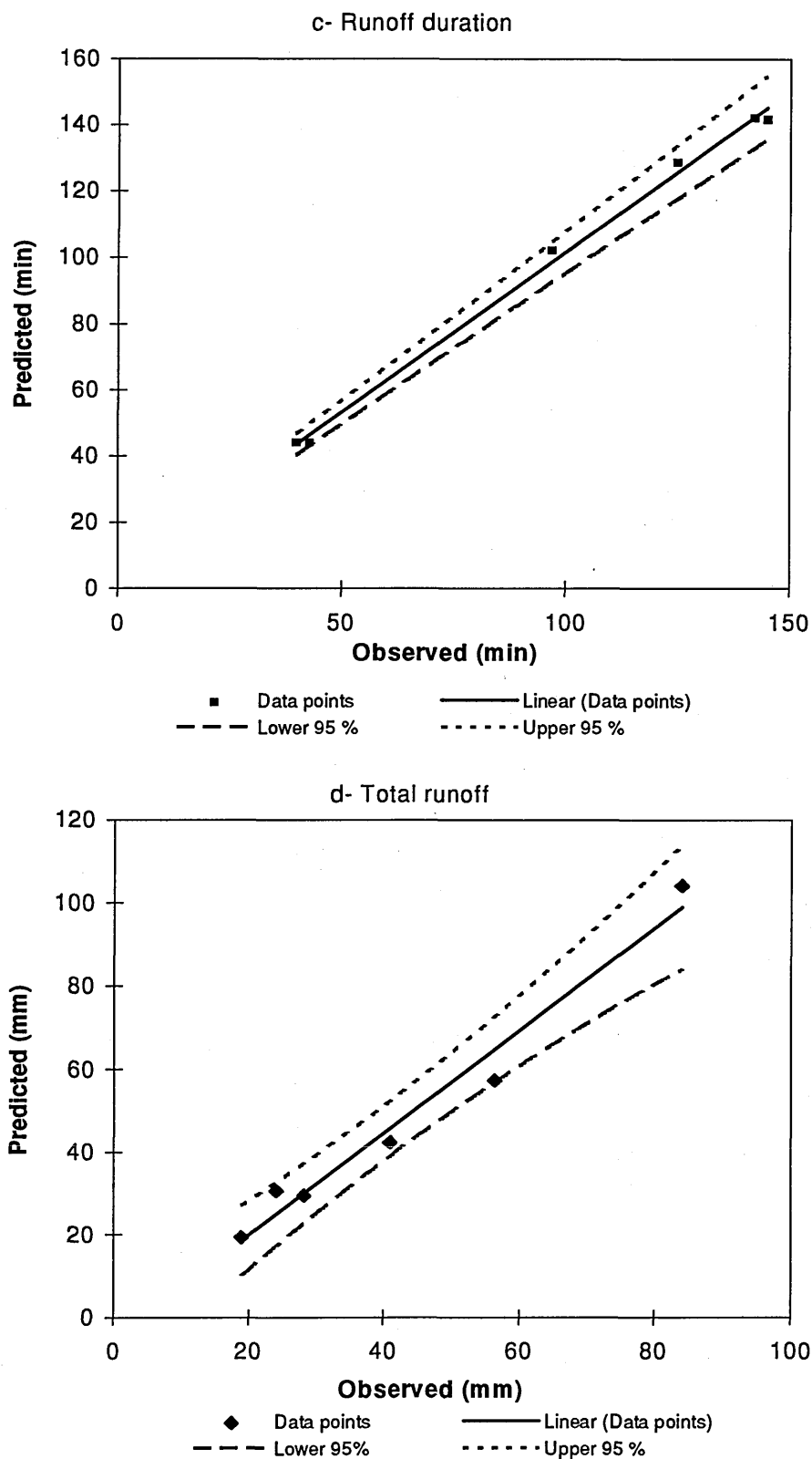


Figure 6.15 Correlation between observed and predicted hydrograph parameters together with confidence limits (contd.)

observed runoff data can be accounted for by each regression line and 3 percent are uncountable. The high values of (R^2) indicate that the regression lines can reasonably be used to represent a good relationship between predicted and observed data.

Two other statistical approaches in Table 6.6 are root mean square error (RMSE) and standard error whose values are small and these can be good indices of agreement between observed and predicted data. Regarding Test 1/ Furrow 6, although the statistical analysis of runoff hydrographs does not approve the correlation between observed and predicted runoff hydrographs, there is visually and statistically good agreement between observed and predicted hydrograph parameters. This will be discussed later on in the next section. Figure 6.14 shows the correlation between predicted and observed runoff data together with confidence bands for lined and unlined furrows. In this figure some of the data points are situated in a horizontal line. This is because the model predictions are the same in the period of equilibrium, while the observed values are different in this period and in the field conditions. In addition to this the observed data were mostly collected at the beginning and at the end of irrigation period. The confidence bands are established around these lines so that these bands will contain the true points at the confidence level of 95 %. From the figures can be seen that the confidence limit is minimum at the mean value of observed data, and it increases when the observed data diverges from the mean.

6.6.4 Statistical analysis of hydrograph parameters

If the observed data in the field confirm the key parameters such as time to runoff, time to peak, time to end, peak flow rate and total runoff then the model may be recommended to use for practical purpose. This should be detected by

statistical analysis. The model validation is completed when the relationship between predicted and observed runoff hydrographs parameters has been judged statistically. For this purpose the predicted hydrograph parameters were firstly plotted against observed data. Figure 6.15 shows the correlation between observed and predicted hydrograph parameters together with their confidence limits. A summary of statistical analysis of hydrograph parameters in the field is also tabulated in Table 6.7. According to this table the correlation coefficients (R) are more than 97 %. This indicates that 97 percent of the total variation in observed hydrograph parameters can be accounted for by each linear line, and 3 percent is uncountable. The high values of (R) indicate that the regression lines can reasonably be used to represent good relationship between predicted and observed parameters. Confidence lines are established around these lines so that these bands will contain the true lines at confidence level of 95 %. It can be seen that the confidence limit is minimum at the mean value of observed data, and it increase when observed data diverges from mean value. According to Table 6.7 model efficiency values are almost one for three parameters and close to unity for the runoff volume. The mean square error and standard error are small (less than 9) for all parameters. So on the basis of this analysis it can be found that there is a good relationship between predicted and observed hydrograph parameters. The relationship between predicted and observed values of time to runoff is acceptable because the corresponding values are zero or approximately close to zero and it is not necessary to do any further statistical analysis.

6.7 Conclusions

On the basis of the above discussion, the following conclusions can be drawn:

1- Model validation was undertaken graphically and statistically using the data collected in the field. There was good agreement between observed and predicted runoff hydrographs and hydrograph parameters.

Table 6.7 A summary of statistical analysis of hydrograph parameters in the field

Test	$\Sigma(\text{predicted-observed})^2$	$\Sigma(\text{Observed -mean observed})^2$	Efficiency	Root mean square error	Equation	Observation	Correlation coefficient (R^2)	Standard Error
	F1	F2	E	RMSE			Calculated	Tabulated
Time to peak	267.1	11035.9	0.976	6.67	$y = 0.9688x + 7.0406$	6	0.993	0.811
Time to end	66.5	11272.6	0.994	3.33	$y = 0.9673x + 4.8961$	6	0.9964	0.811
Peak flow rate	30.3	1108.469	0.97	2.25	$y = 0.9061x + 2.286$	6	0.9826	0.811
Total runoff	445.2	3009.3	0.852	8.61	$y = 1.2359x - 4.9021$	6	0.9734	0.811

Slope		Intercept			
a	Lower 95%	Upper 95%	b	Lower 95%	Upper 95%
Time to peak	0.969	0.86	1.08	7.041	-0.17
Time to end	0.967	0.89	1.05	4.9	-3.76
Peak flow rate	0.906	0.74	1.07	2.286	-3.77
Total runoff	1.2	0.95	1.5	-4.9	-18.4

2- Hydrograph analysis shows that the slope of accumulated runoff is an indicator of rainfall and soil characteristics. From this can be found that the dominant factor in runoff creation is water application rate. So the danger of surface runoff and soil erosion is greater next to the line source sprinklers where the water application rate is maximum. Therefore, the soil and water conservation structures may required to be built along the furrows which are under higher application rates due to their closeness to the line source sprinkler.

3- The infiltration capacity of water into soil under various application rates of sprinkler irrigation is less than that of under flood irrigation. This difference is also valid for basic infiltration rate at different application rate. So the flood irrigation methods are not suitable for the determination of infiltration rate under sprinkler conditions.

The infiltration rate of even a given soil not only changes with time and application rate but also changes with the frequency of irrigation during the season. As a result the infiltration rate is the most changeable factor which must be determined for a specific situation for the prediction of surface runoff

It seems that the falling head infiltrometer may be suitable for measuring the basic infiltration rate under sprinkler irrigation conditions. Using this method can save time and money. Further investigation is required to determine the best method of measuring infiltration rate under sprinkler irrigation.

4- Runoff coefficient not only changes with time during each irrigation event, but also changes with the number of previous irrigations. As a result, the water application rate for each irrigation following the previous one should be declined in order to reduce or prevent runoff. Even the water application rate at the mean time of irrigation should be less than that of at the beginning of each irrigation event to reduce runoff.

CHAPTER 7

MODEL VALIDATION FOR MOBILE SPRINKLERS IN FIELD

7. Model Validation for Mobile Sprinklers in Field

7.1 Introduction

This section describes a field experiment undertaken to validate the model developed in chapter three. This involved both ridge and furrow cultivation and plane sloping surfaces. The soil was sandy loam, similar to that used for the stationary sprinkler evaluation. Water was applied using a moving sprinkler, a Nelson 8401 Rain Train traveller with a rotary impact sprinkler with a 6 mm nozzle (Figure 7.1). Table 7.1 describes the moving sprinkler characteristics. During early trials the application rate from the sprinkler was insufficient to cause runoff. To overcome this problem the sprinkler sector angle was reduced considerably from 360° down to 18°. This increased the application rate substantially so that runoff occurred. Unfortunately the narrow sector angled spray was easily distorted by the wind and this affected both the application rate on the plots and the runoff.

Tests were conducted on two types of cultivation, a plane sloping surface and ridge and furrow cultivation with plots running down the main slope. The

Table 7.1 Characteristics of the moving sprinkler*

Factor	Value	Unit
Average nozzle pressure	3	bar
Average discharge	0.308	l / s
Nozzle diameter	6	mm
Sector angle	18	degree
Height of riser	1000	mm
Average throw diameter	24	m

* Sprinkler type was a Nelson 8401 Rain Train traveller fitted with a rotary impact sprinkler



Figure 7.1 A type of Nelson 8401 Rain Train Traveller and runoff generation on soil surface under a moving sprinkler

basic information related to the experimental plots are summarized in Table 7.2. Words in column 1 refer to experimental plots that may be ridge and furrow (Furrow) or plane sloping surface (Basin) and numbers refer to their location in site as indicated in Figure 7.2.

Although runoff measurement from a simple ridge and furrow cultivation was the principle aim of the experiment, additional furrows were constructed and various runoff reduction measures were incorporated to test their effectiveness. These included tied ridges, mulching in the base and sides of furrow and pitting.

In order to use the KINEROS-EUROSEM model, there are several parameters which need to be measured at the field site or laboratory. The application rate was measured during the experiments using a row of catch cans along the throw radius. Figure 7.3 shows a spray pattern from the moving sprinkler in a stationary position for a sector angle of 18 degrees. The catch can data and the calculation of average water application rate are presented in Appendix E.1. Generated surface runoff was measured at the end of furrows and basin during each experiment by using volumetric method.

Table 7.2 Basic information of experimental plots

Plots	Length (m)	Width (mm)	Slope (%)	Texture	Condition	Roughness ratios (%)	
						across slope	along slope
						(ASR)	(RFR)
Validation test:							
Furrow 4	12	90	4	sandy loam	Free	18.2	1.0
Furrow 6	12	90	4	sandy loam	Free	18.2	1.0
Basin 1	12	3200	4	sandy loam	Free	1.1	1.0
Runoff reduction measures:							
Furrow 1	12	90	4	sandy loam	Mulched	18.2	1.1
Furrow 2	12	90	4	sandy loam	Tied	18.2	23.1
Furrow 3	12	90	4	sandy loam	Pitting	36.0	23.1

Note: The data related to the Furrow 5 was not reliable and so it was ignored

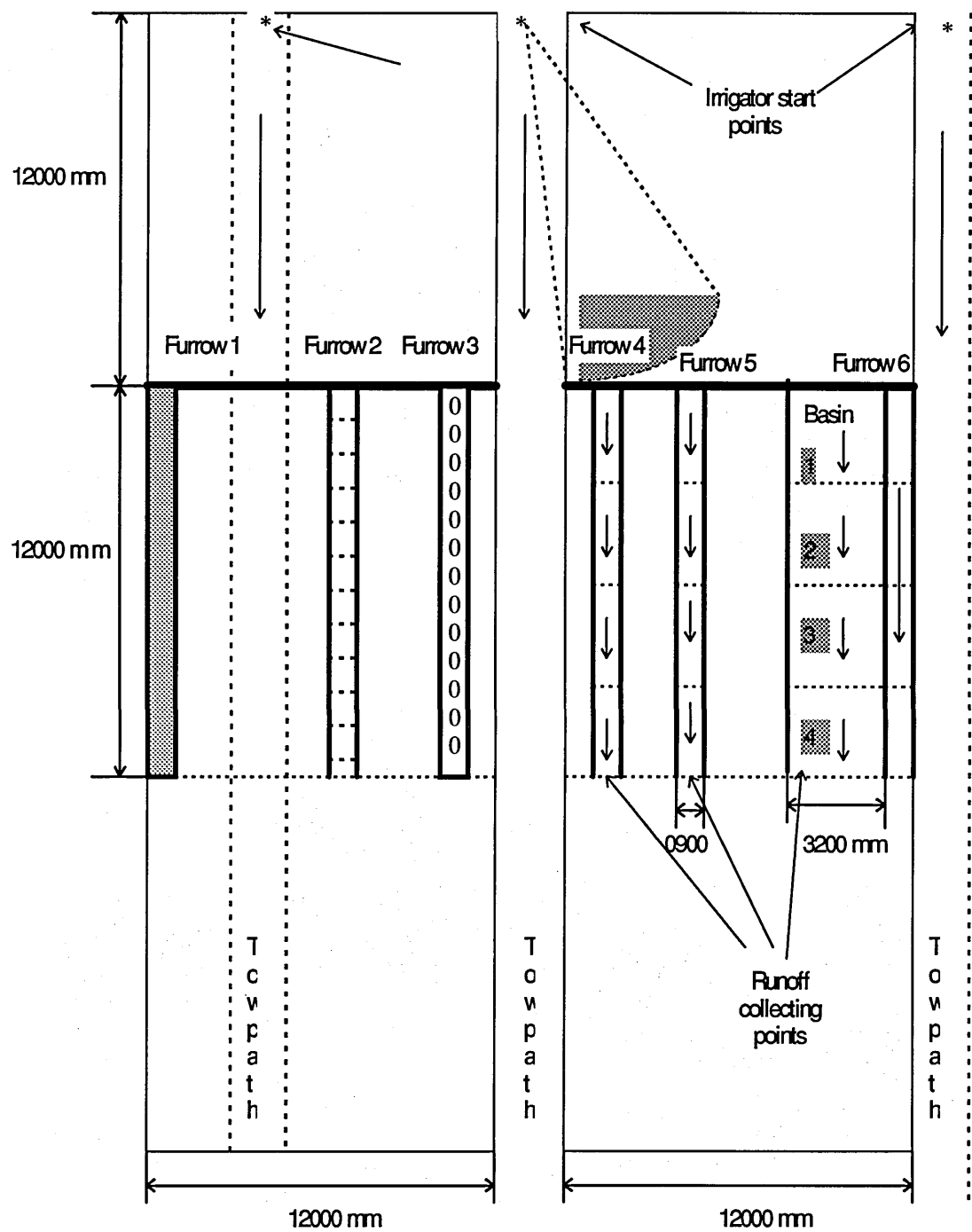
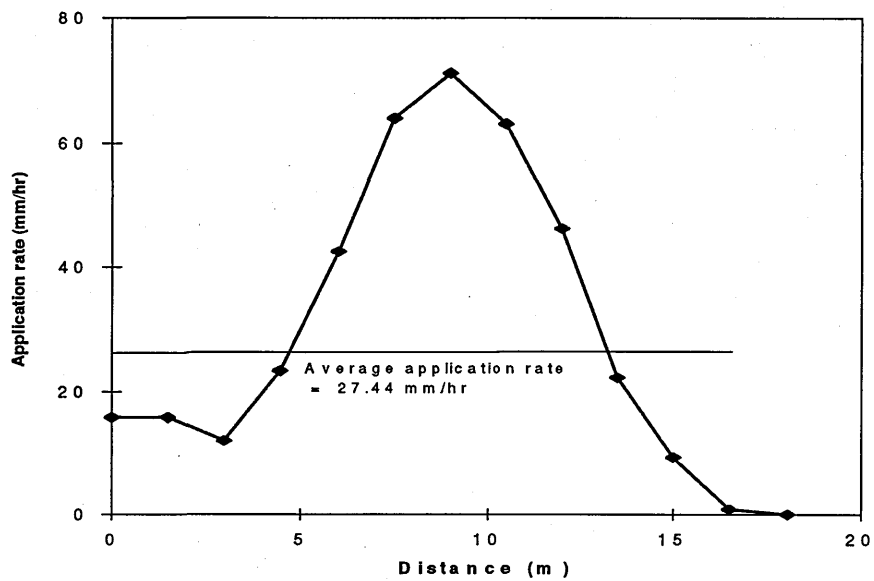
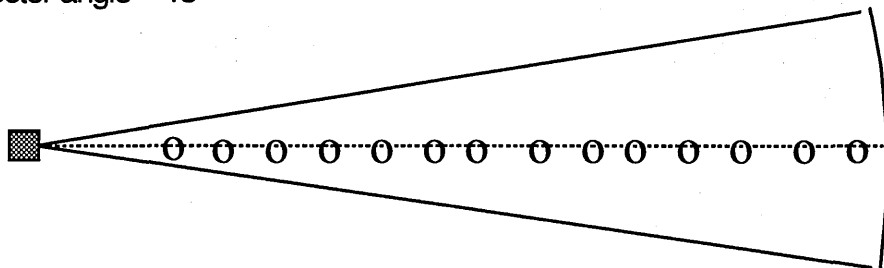


Figure 7.2 Experimental layout in field



(a)

Sector angle = 18°



O Collector

■ Moving sprinkler

(b)

Figure 7.3 (a) A spray pattern from the moving sprinkler in a stationary position and (b) collectors along the wetted radius.

The values of saturated hydraulic conductivity of the soil under sprinkler irrigation were estimated by using soil infiltration capacity curves resulted from water balance equation. The furrow infiltrometer method was also used to measure the infiltration capacity in the field after running each experiment. Since the experimental plots were under sprinkler irrigation, the estimated hydraulic conductivity values for the second and the third irrigation by this method were close to those values measured under sprinkler condition using water balance equation (Figure 7.4 and Table 7.3).

Initial soil water content was measured in order to use as input to the model. Final soil water content was also measured for the assessment of runoff effect on soil water distribution along the slope. To find these factors, soil samples were taken from depths, 0-100, 100-200 and 200-300 mm before and at least 24 hours after each experiment. The water content was measured in the laboratory using the gravimetric method. The same calibrated capillary drive value obtained for stationary sprinkler validation was used for model validation in moving sprinkler conditions. The tests were carried out for different application rates and low, medium and high travel speeds. Table 7.3 shows the typical soil and water application characteristics related to the field experiments at various travel speeds. The travel speed of the machine was controlled by adjusting the water flow through the system by using a valve. When the valve was opened more water passed through the drive system and the machine moved faster.

7.2 Simulation procedure

As described in section 3.15 runoff could be simulated for a moving sprinkler by dividing a catchment into a number of elements that have the equal length. These elements are assumed to be rectangular. The length of elements affects the smoothness of simulated runoff hydrograph. The smaller the

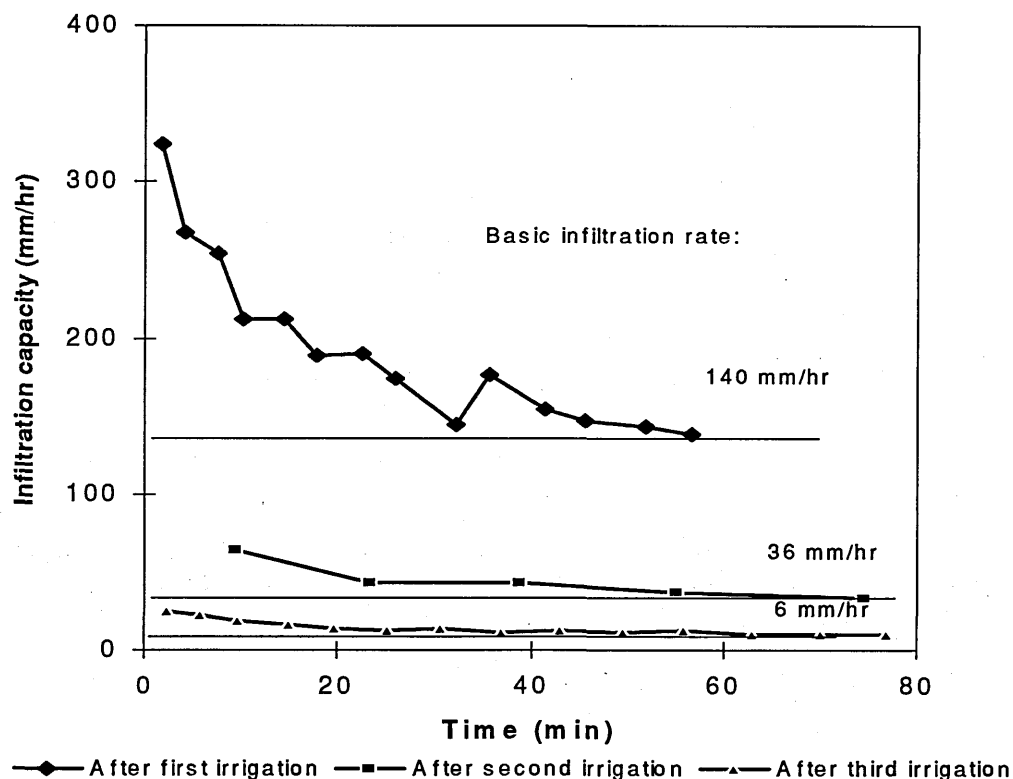


Figure 7.4 Soil infiltration capacity curves

Table 7.3 Typical soil and water application characteristics related to the field experiments at various travel speeds.

Plot	Test No.	Travel speed (V) (m/hr)	Average application rate (R_{av}) (mm/hr)	Average soil water content (θ_{av}) (%)	Application time (T_a) (min)	Hydraulic conductivity (K) (mm/hr)
Evaluation:						
Furrow 6	Test 1	3.4	42	7	210	30
Furrow 6	Test 2	7.9	21	21.5	83.5	6
Furrow 6	Test 10	12.2	35	17.2	61.3	6
Furrow 4	Test 3	6.8	25	13.3	105.9	18
Furrow 4	Test 5	19	23	15.4	38	4
Basin 1	Test 7	11.3	27	16.5	61.1	23.5
Basin 1	Test 11	12.2	35	17.5	61.3	12
Runoff reduction measures:						
Furrow 1	Test 9	12.9	31	14.3	56	40
Furrow 2	Test 8	12.9	27	10.4	56	34
Furrow 3	Test 6	19	17	12.5	37.9	34

element length, the smoother the resulting simulated hydrograph. The steps in runoff hydrograph show the number of elements in a catchment in which the soil and water characteristics are uniform. Figure 7.5 shows simulated hydrographs resulting from a hypothetical catchment whose length is divided into elements having 6, 3 and 2 meters length (see section 3.15). According to this figure there is a considerable discrepancy between the hydrographs of 6 and 3 meter length element but there is not so much difference between the hydrographs resulting from the elements of 2 and 3 meters lengths. Therefore, the length of 3 meter was the optimum value which was chosen to simulate the runoff from a moving sprinkler in the field experiments. This procedure was followed for both simple plane and ridge and furrow. Figure 7.6 shows a 12 meter length simple catchment which was divided into four elements. A ridge and furrow was assumed to be a catchment.

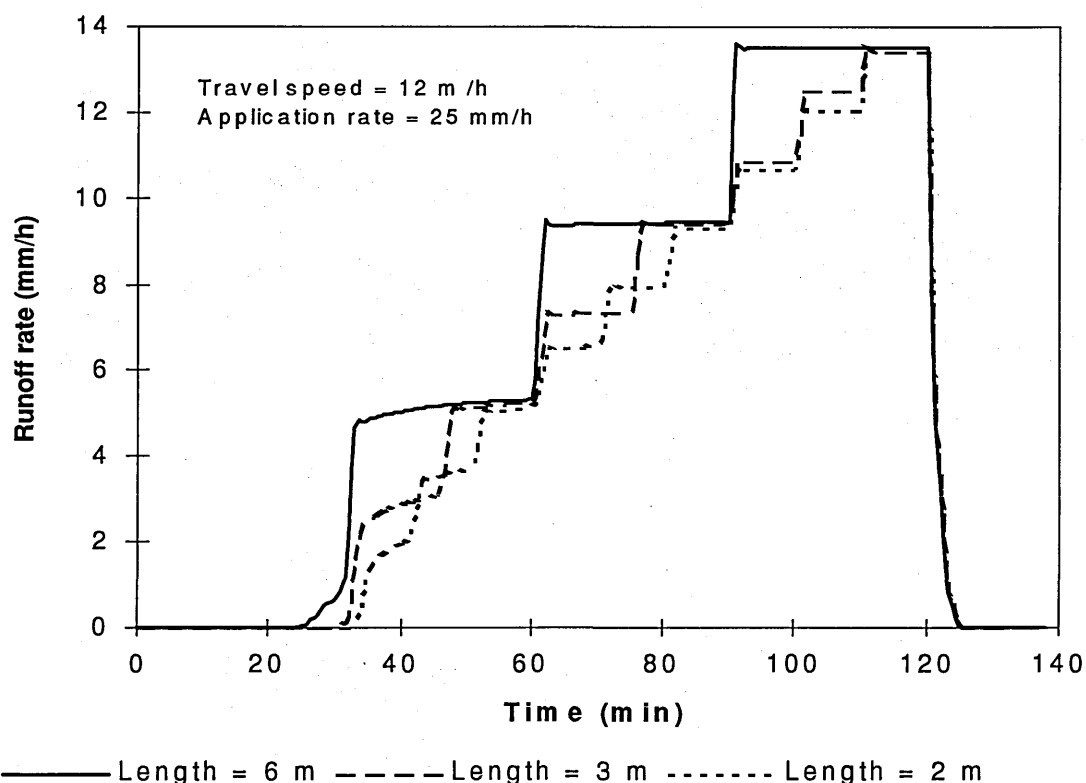


Figure 7.5 Simulated runoff hydrographs for a moving sprinkler for different length of elements

that comprises of three sub-catchments, two sides and one bed. The sides and bed were also divided into a number of equal elements (Figure 7.7). The numbers and arrows show the arrangement of elements and the direction of the runoff from one element to the next element respectively.

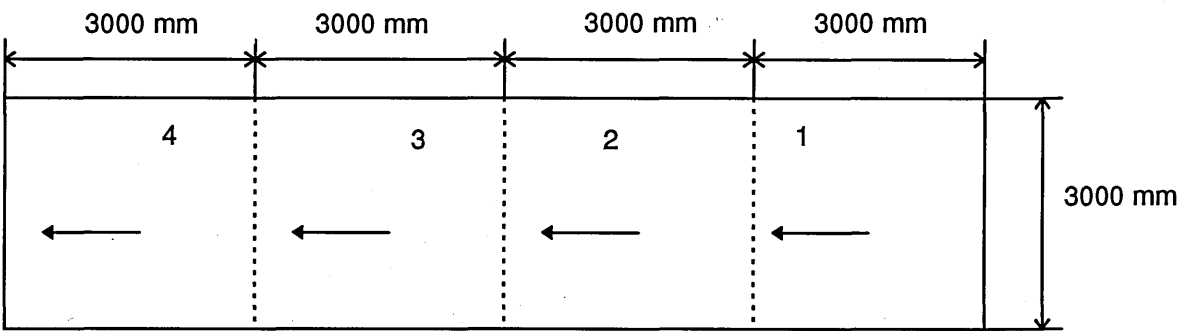


Figure 7.6. Division of a simple plane micro-catchment into elements.

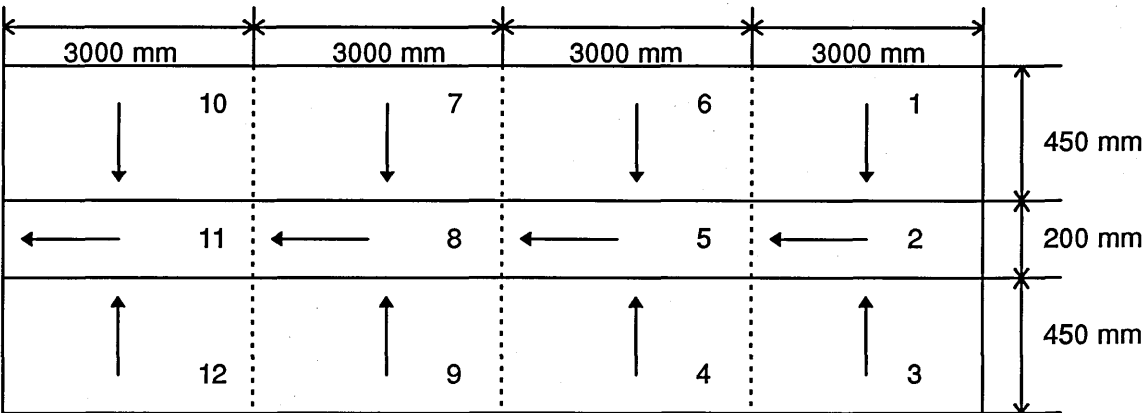


Figure 7.7. Division of a ridge and furrow micro-catchment into elements.

When an irrigator moves along a catchment the water application pattern (WAP) moves as well. There is a time interval between the beginning and end of a WAP when it passes over the beginning and end of a catchment. The length of time depends on the speed of irrigator. The more the speed the less the water application depth on and surface runoff from that element.

7.3 Comparison between simulated and observed runoff

The basis of the comparison between simulated and observed runoff hydrographs for moving conditions is the same as for stationary conditions. That is the same parameters (time to start runoff, time to peak, time to end , peak flow rate, the volume of runoff and runoff hydrographs) are used for this purpose. The importance of these parameters has been discussed in chapters 5 and 6. So the comparison between runoff hydrographs shows generally how the model simulates the runoff hydrograph and related parameters.

7.3.1 Individual tests

In this section each test is discussed individually and a comparison is made between the field results and model simulations. Figure 7.8 shows the comparison between observed and predicted runoff hydrographs for experimental plots. The values of observed and corresponding simulated hydrograph parameters are also presented in (Table 7.4).

The charts (a), (b) and (c) from Figure 7.8 show runoff hydrographs in furrow 6. Although the travel speed for the first test is low (3.4 m/hr) and average water application rate is high (42 mm/hr), runoff starts much later and peak flow rate is smaller compare to the two other runoff hydrographs. This is because the soil was quite dry (soil water content = 7%) for the first irrigation event and there was no crust on the soil surface so that the hydraulic conductivity was high. The soil water content has a positive effect and hydraulic conductivity has the negative effect on runoff. The sensitivity of peak flow rate and runoff volume to the soil water content and the hydraulic conductivity is also high (see section 5.2.2 and 5.2.3). This is why the peak flow rate and runoff volume of the chart (a) is lower than that of chart (b) and (c). Overall, visually there is a good agreement between observed and

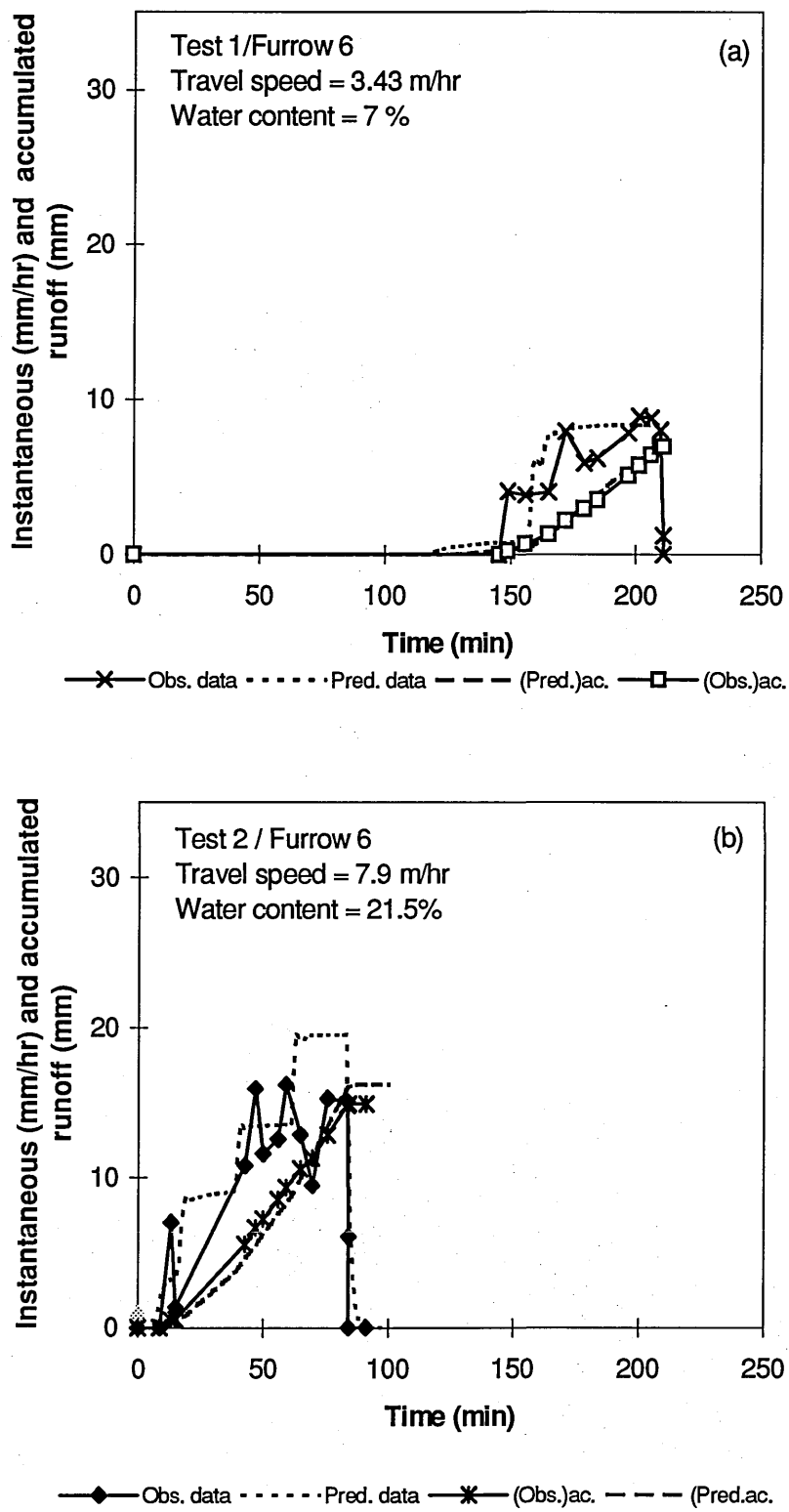


Figure 7.8 Comparison between observed and predicted runoff hydrographs for a moving sprinkler.

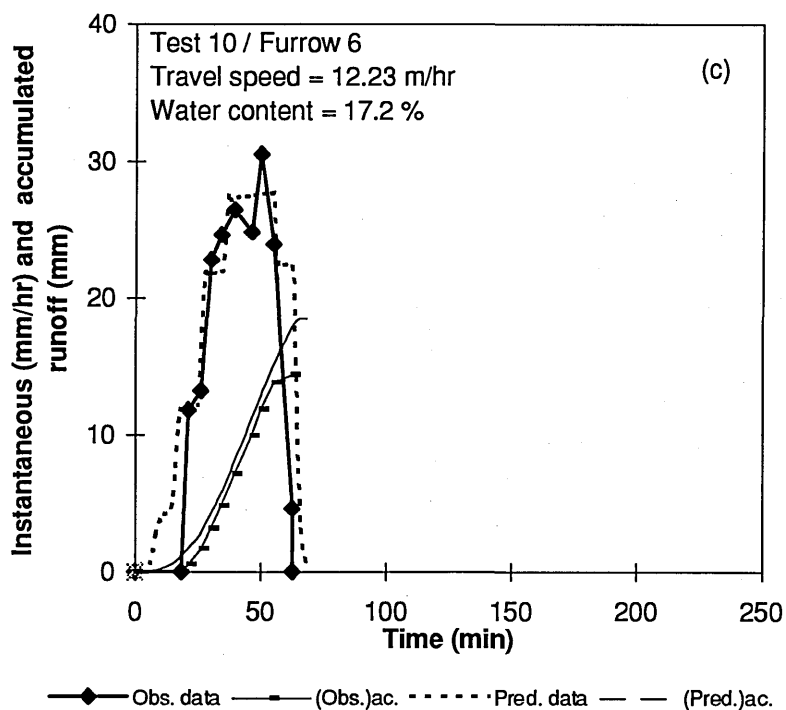
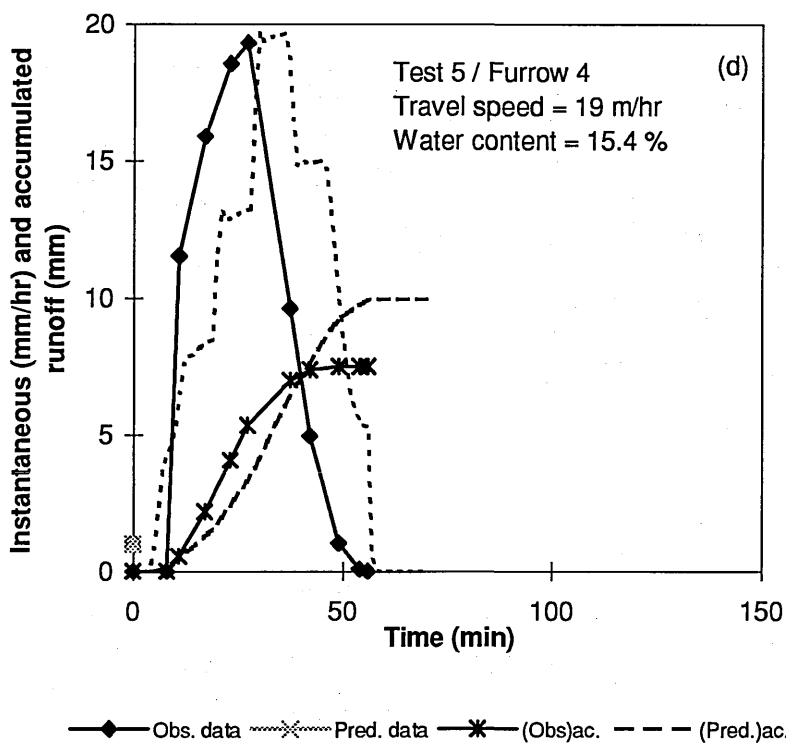


Figure 7.8 Comparison between observed and predicted runoff hydrographs for a moving sprinkler (contd.)

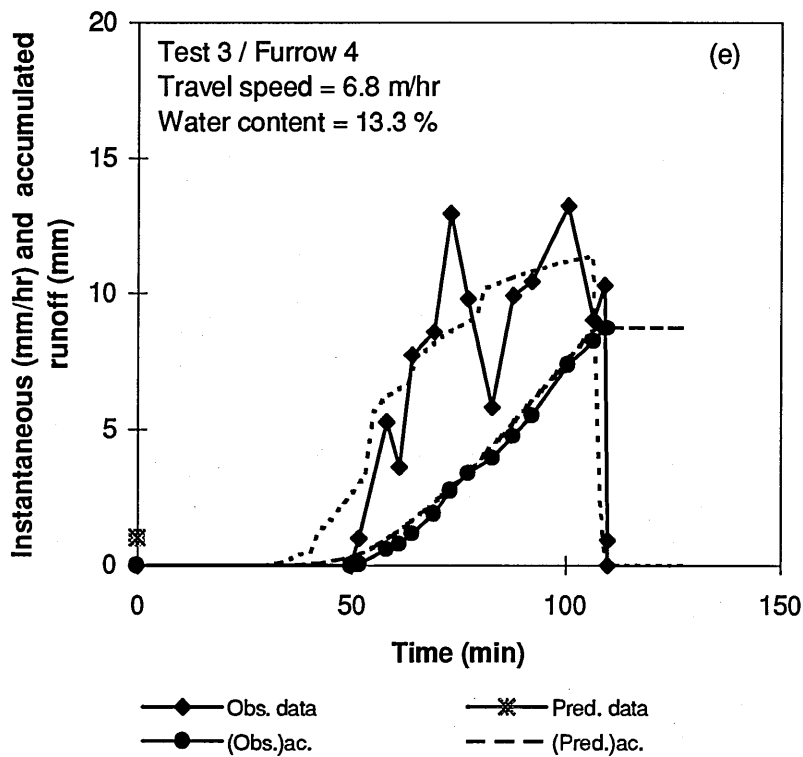
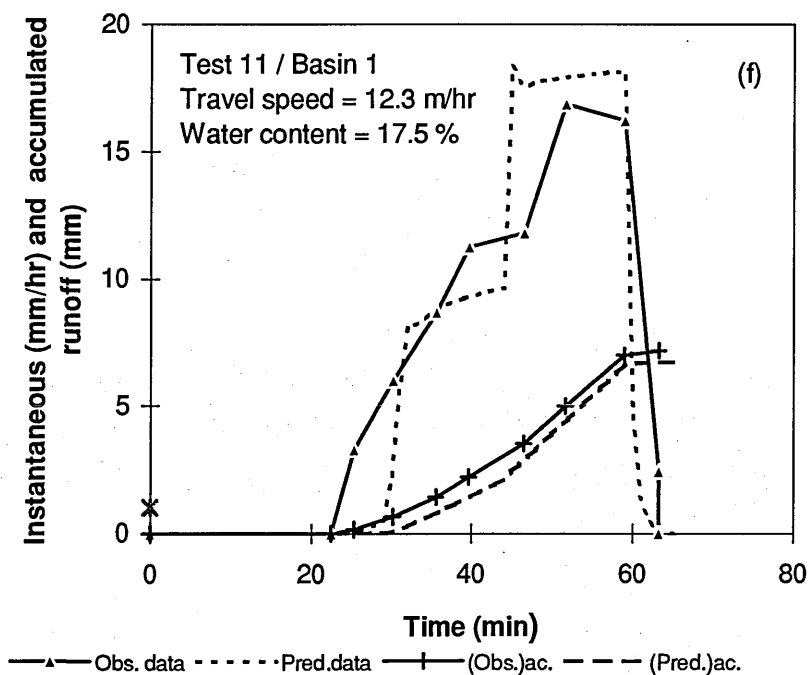


Figure 7.8 Comparison between observed and predicted runoff hydrographs for a moving sprinkler (contd.)

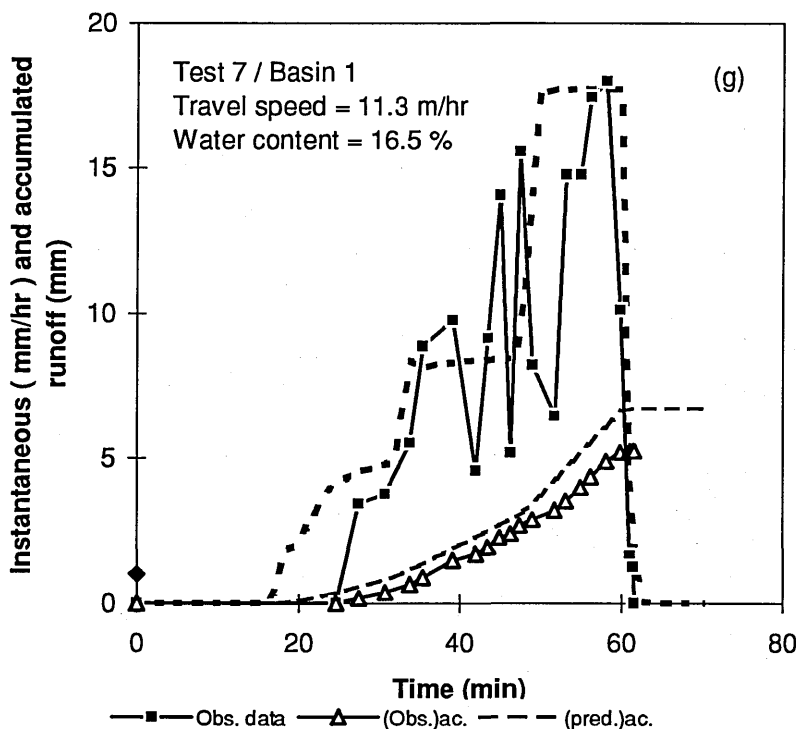


Figure 7.8 Comparison between observed and predicted runoff hydrographs for a moving sprinkler (contd.)

predicted runoff hydrographs (charts a, b and c) and corresponding parameters. Charts (d) and (e) in Figure 7.8 show the runoff hydrographs from furrow 4. Although the water application rate and the soil water contents for the conditions shown these two charts are nearly same (Table 7.3), the travel speed for chart (e) conditions (6.8 m/hr) is much smaller than that for chart (d) conditions (19 m/hr). It is expected that the time to start runoff for chart (e) to be much earlier than for chart (d) conditions but it is opposite. This is because the test related to chart (e) was carried out before the test related to chart (d) on Furrow 4 and the irrigation event number has a negative effect on the hydraulic conductivity of the soil. Therefore, the hydraulic conductivity of the test related to the chart (e) (18 mm/hr) is greater than the hydraulic conductivity of the test related to the chart (d) (4 mm/hr). The lower hydraulic

Table 7.4 Parameters describing observed and predicted runoff hydrographs.

Test No/plot No	Type	Travel speed (V) (m/hr)	Average application rate (mm/hr)	Hydraulic conductivity (K) (mm/hr)	Capillary drive (G) (mm)	Time to runoff (T _r) (min)	Time to peak (T _p) (min)	Peak flow rate (Q _p) (mm/hr)	Duration of runoff (T _d) (min)	Volume of runoff (Q _v) (mm)
Evaluation:										
Test 1 / Furrow 6	Predicted	3.4	210	30	11	119	210	8	92	7
	Observed		210			146	202	9	66	7
Test 2 / Furrow 6	Predicted	7.9	83.5	6	11	6	63	20	86	16
	Observed		83.5			9	59	16	75	12
Test 10 / Furrow 6	Predicted	12.2	61.3	6	11	5	46	29	67	18
	Observed		61.3			19	50	30.5	44	14
	Observed		38			5	23	21	33.5	14
Test 7 / Basin1	Predicted	11.3	61.1	23.5	11	17	49	14	48	5
	Observed		61.1			25	58	18	37	8

Table 7.4 (contd.)

Test No/plot No	Type	Travel speed (V) (m/hr)	Average application rate (mm/hr)	Hydraulic conductivity (K) (mm/hr)	Capillary drive (G) (mm)	Time to runoff (T _r) (min)	Time to peak (T _p) (min)	Peak runoff rate (Q _p) (mm/hr)	Duration of runoff (T _d) (min)	Volume of runoff (Q _v) (mm)
Test 11 / Basin1	Predicted	12.2	61.3	12	11	24	45	18	40	7
	Observed		61.3			22.5	52	17	41	7
Test 3 / Furrow 4	Predicted	6.8	106	18	58	31	106	11	79	9
	Observed		106			50	100.5	13	60	8
Test 5 / Furrow 4	Predicted	19	38	4	11	3	29	17	49	9
	Observed		38			8	27	19	48	10
Runoff reduction measures:										
Test 9 / Furrow 1	Predicted	12.9	56	40	11	No	runoff			
	Observed		56							
Test 8 / Furrow 2	Predicted	12.9	56	34	11	No	runoff			
	Observed		56							
Test 6 / Furrow 3	Predicted	19	38	34	11	No	runoff			
	Observed		38							

conductivity causes runoff to occur much earlier and also increases the peak flow rate and runoff volume. Charts (f) and (g) from Figure 7.8 show runoff hydrographs from basin 1. Although the travel speed and the soil water contents for the conditions of these two charts are nearly same (Table 7.3), their water application rate and the hydraulic conductivity are different. Regarding the negative effect of hydraulic conductivity and positive effect of water application rate on peak flow rate and the volume of runoff, their effects will be neutralized so that not only the peak flow rate of two hydrographs but other parameters of the hydrographs becomes more or less same. Overall, the field results visually match the model results successfully.

7.3.2 Overall comments

From the Figure 7.8 and the Table 7.4 can be found that the time to start runoff of simulated hydrographs is shorter than that of measured hydrographs. This trend is almost the same for all hydrographs. However, to see how significant the discrepancy between observed and predicted time to runoff is, statistical analysis is needed which will be discussed in the next section.

Time to ending runoff is another hydrograph parameter. The model simulates this parameter for 5 of 7 experiments very closely. However, there is a little difference between observed and predicted time to end runoff in tests number 2 and 10 (Figures 7.8). This may be due to random errors, such as non straight traveller pathway or muddy pathway where these two experiments were run. Duration of runoff can be determined by subtracting time to end runoff from time to start runoff (the magnitude and the simulation quality of this factor highly depends upon two former parameters. Regarding the discussion about two previous parameters, agreement between observed and predicted duration of runoff is more than time to start runoff and less than time to ending runoff).

The observed and predicted time to peak runoffs are also associated in Figure 7.8. The values of this parameter are also presented in Table 7.4. The difference between observed and related simulated values is small. The comparison between observed and simulated peak flow rates shows higher predicted values for all the experiments. This may be a positive aspect of the model for designing and water management purposes.

Total runoff (volume) was determined by measuring the areas under the instantaneous observed and simulated runoff hydrographs. Two techniques, trapezoid and grid square methods, were used to determine the area under curves. The data presented in Table 7.4 shows the simulated values are a little higher for 5 of 7 experiments and lower for the rest 2. The total accumulated observed and predicted runoff can also be compared by using the accumulated runoff hydrographs in the Figure 7.8. Visually there is good agreement between them.

The fluctuation in the observed hydrographs is mainly due to partial rotation of sprinkler and narrow sector angled spray that seriously affected by wind speed and direction. Even in gentle weather wind distortion was observed.

Overall, there is visually good agreement between the simulated and observed runoff hydrographs and corresponding parameters for a moving sprinkler. Therefore, the model can predict runoff and the related parameters very well. Further statistical analysis is required to confirm this discussion.

7.4 Statistical analysis

Correlation analysis and the model efficiency techniques were used to analyze the data in this study. In these techniques, the simulated hydrographs data are compared to the observed hydrographs data. Further tests were

Table 7.5 Statistical analysis of observed and predicted runoff hydrographs .

Test	Observation	Coefficient of efficiency				Correlation analysis		
		(F1) =		(F2) =		Equation	Slope (a ₁)	
		No. of data	$\Sigma(\text{predicted-observed})^2$	$\Sigma(\text{Observed-mean observed})^2$	Efficiency		Main value	(Lower Upper Limit) _{95%} Limit) _{95%}
Furrow 6/Test 1	14	201	44	0.784	y = 1.031x + 0.0193	1.031	0.692	1.369
Furrow 6/Test 2	16	547	395	0.278	y = 0.8467x + 3.3484	0.847	0.409	1.284
Furrow 6/Test 10	15	1933	1069	0.447	y = 0.6771x + 8.265	0.667	0.353	1.001
Furrow 4/Test 3	18	388	166	0.573	y = 0.7022x + 1.56	0.702	0.395	1.009
Furrow 4/Test5	11	624	174	0.721	y = 0.7509x + 2.4672	0.751	0.405	1.097
Basin 1/Test 7	23	787	372	0.527	y = 0.8194x + 2.9646	0.819	0.545	1.094
Basin 1/Test 11	11	409	69	0.831	y = 1.181x - 1.4227	1.181	0.903	1.459
Intercept (a ₀)		Correlation coefficient (R ²)			Standard error			
Main value	(Lower limit) _{95%}	(Upper limit) _{95%}	Calculated	Tabulated	Confidence			
0.0193	-1.93	1.969	0.887	0.661	at 95%	1.89		
3.348	-1.285	7.982	0.743	0.497	at 95%	4.77		
8.265	2.979	13.551	0.781	0.661	at 90%	6.60		
1.560	-0.774	3.894	0.772	0.456	at 95%	2.85		
2.467	-1.173	6.107	0.854	0.602	at 95%	3.82		
2.965	0.357	5.571	0.805	0.413	at 95%	3.70		
-1.423	-3.991	1.145	0.955	0.602	at 90%	2.48		

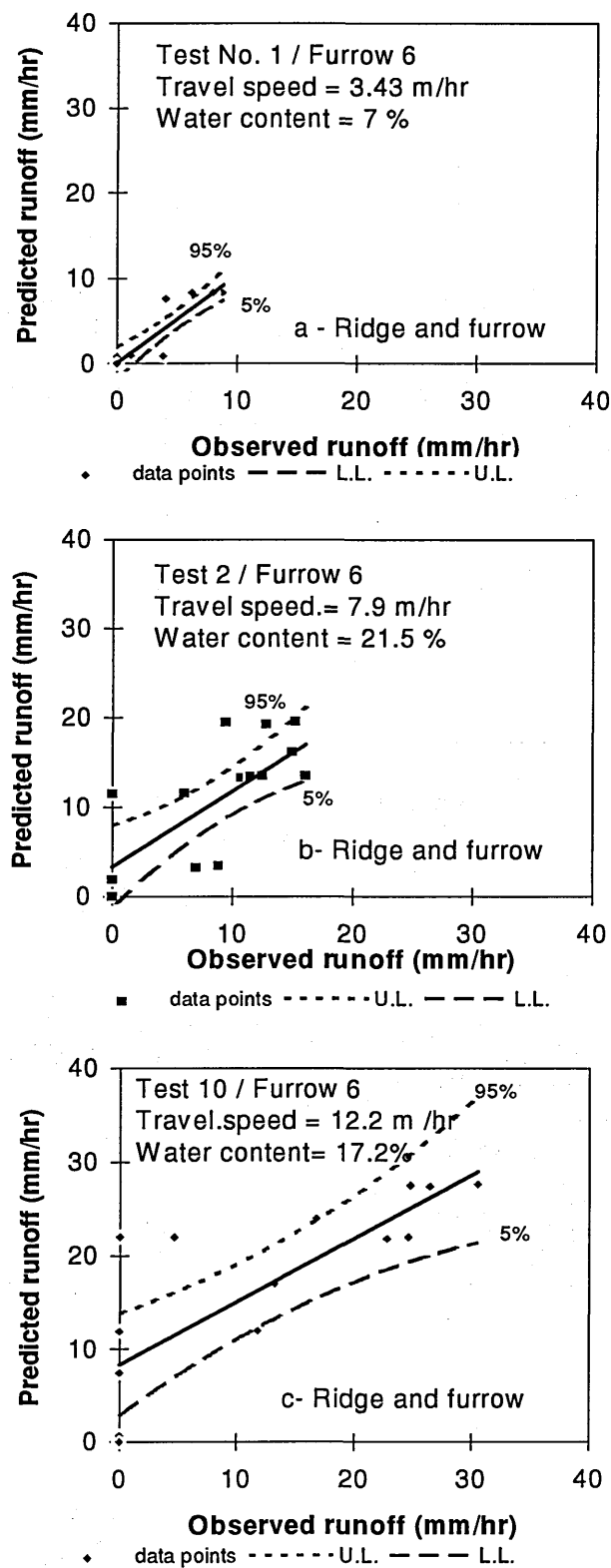


Figure 7.9 Correlation lines and confidence limits for runoff hydrographs.

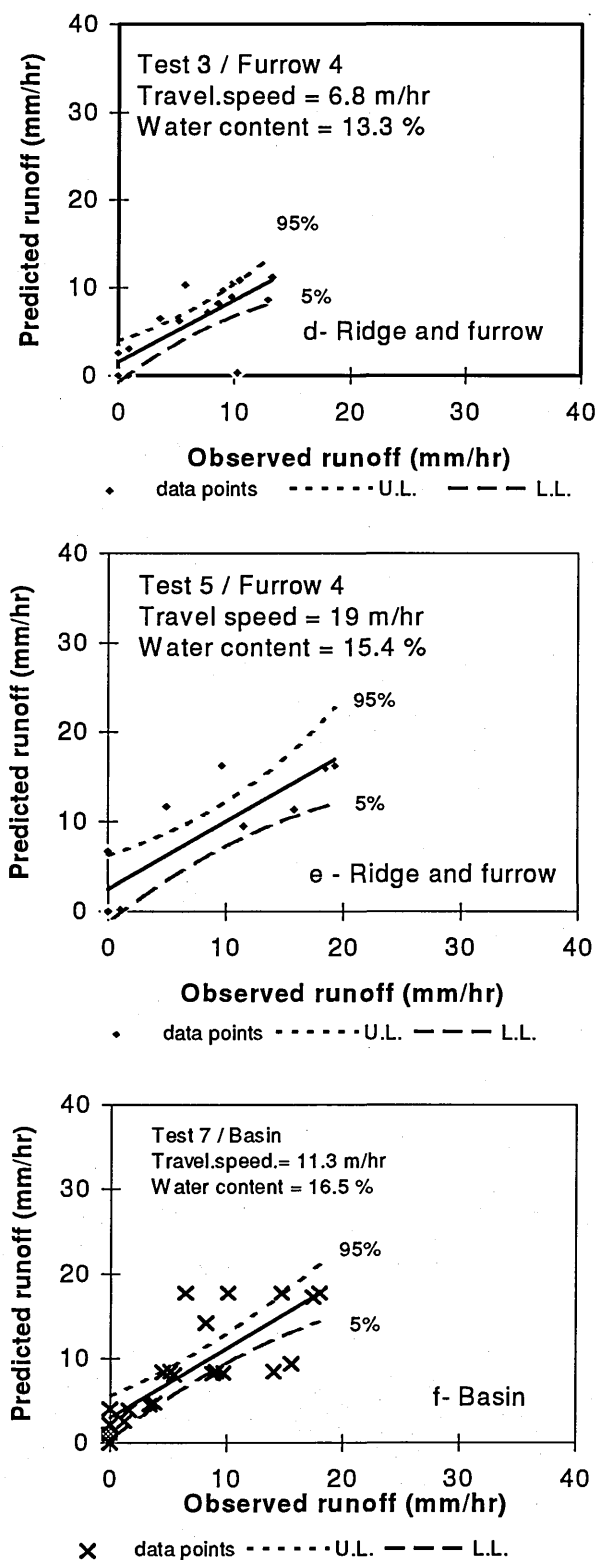


Figure 7.9 Correlation lines and confidence limits for runoff hydrographs (contd.)

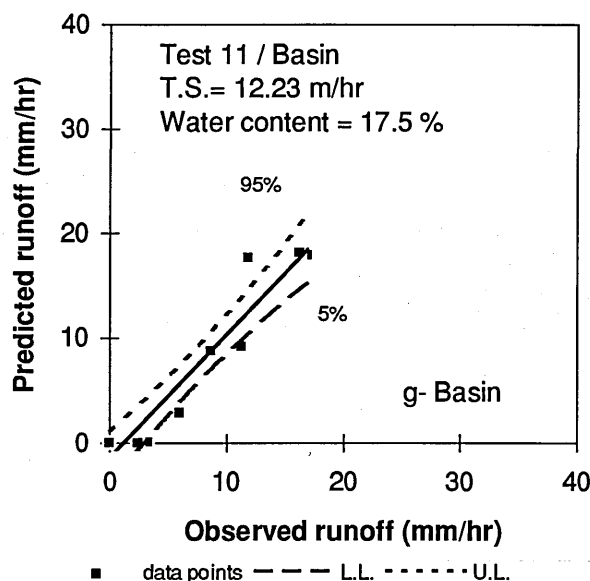


Figure 7.9 Correlation lines and confidence limits for runoff hydrographs (contd.)

carried out by comparing the calculated correlation coefficient with standard test tables. The confidence intervals of the best fit lines, slopes and intercepts were determined at the level of 95%. A summary of statistical analysis of hydrographs are presented in Table 7.5. Figure 7.9 also shows the correlation lines together with the 95% confidence limits between observed and predicted runoff hydrographs at different travel speeds.

Figure 7.10 shows the correlation lines together with 95 % confidence limits between observed and predicted hydrograph parameters. These parameters are: time to runoff, time to peak runoff, duration of runoff, peak flow runoff and total runoff depth. The hydrograph parameters are analyzed by the same statistical techniques. A summary of the statistical analysis of hydrograph parameters is presented in Table 7.6. According to this table the coefficients of efficiency values of time to peak and time to start runoff, are close to unity;

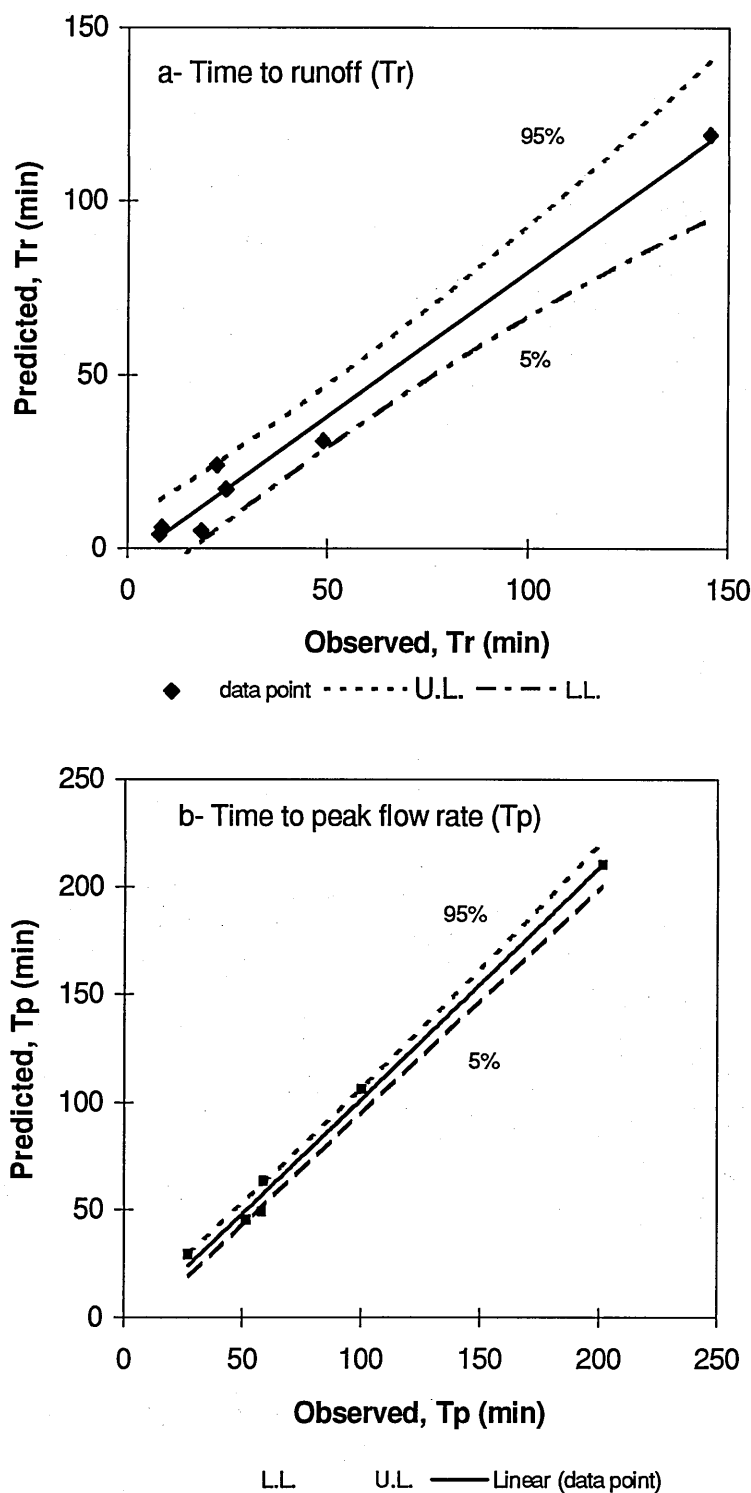


Figure 7.10 Correlation lines and confidence limits for hydrograph parameters.

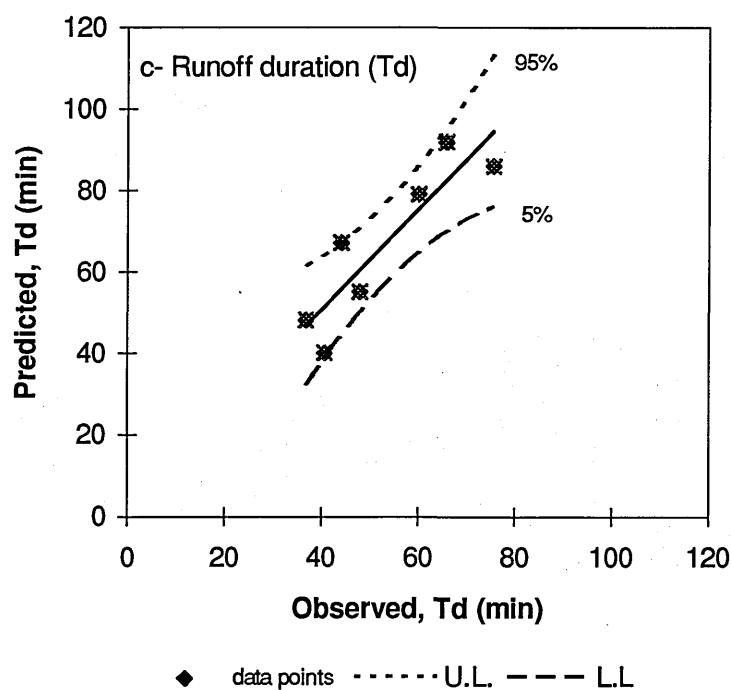
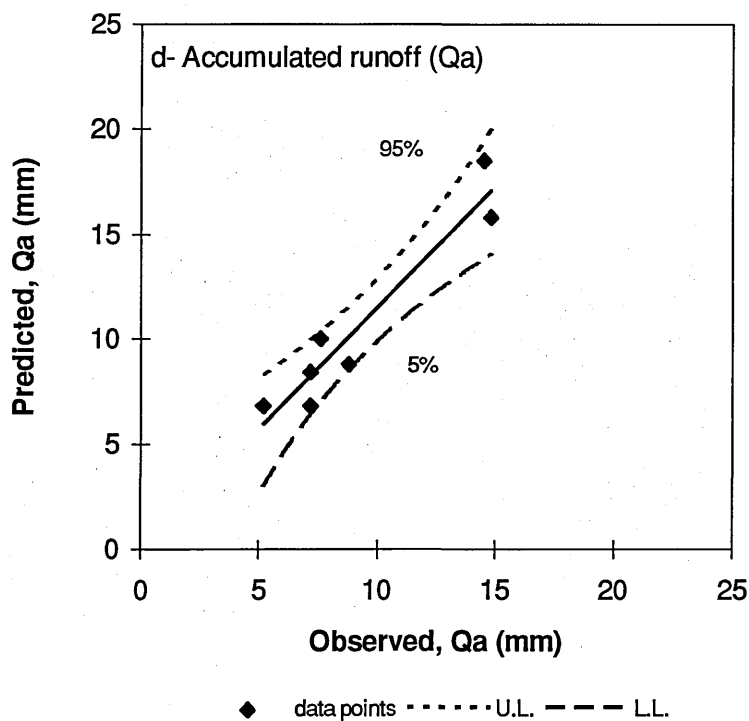


Figure 7.10 Correlation lines and confidence limits for hydrograph parameters (contd.).

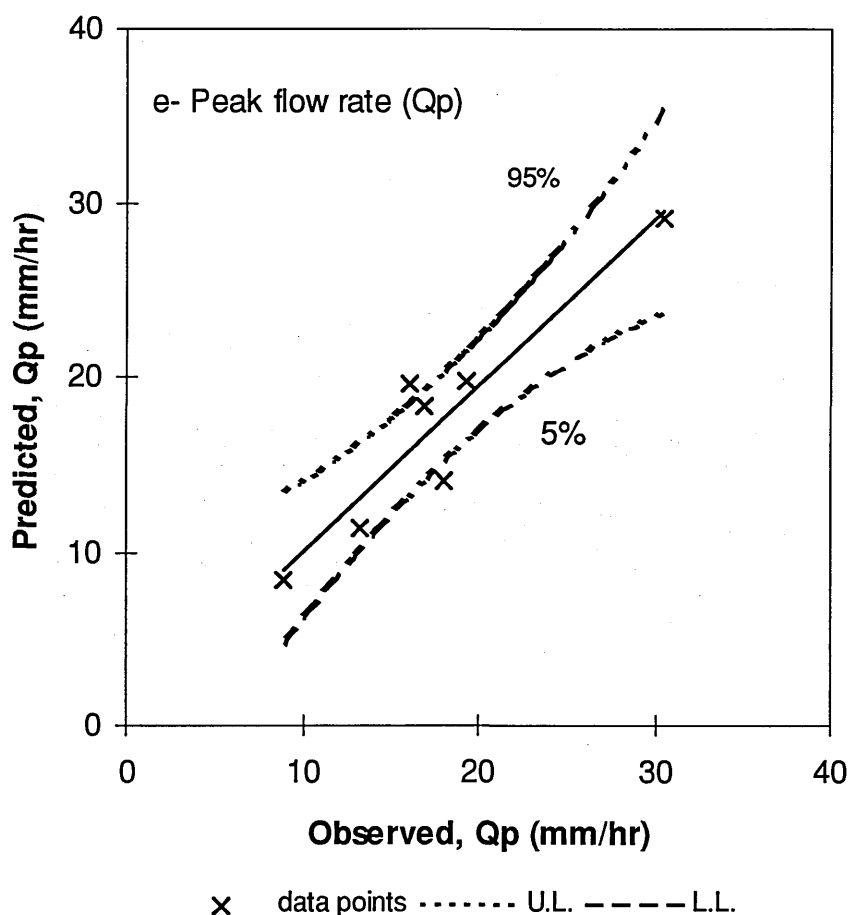


Figure 7.10 Correlation lines and confidence limits for hydrograph parameters (contd.)

but they are less than 0.90 for the rest. Therefore, it is important to find firstly whether there is any association between observed and predicted parameters; secondly whether the slope of best fit line and intercepts are significantly different from unity and zero respectively. To find the answers to these questions, the correlation analysis was performed. The correlation analysis test shows good agreement between parameters; because the correlation coefficient (R^2) values are more than 0.9 at 95% confidence level. For example: for the time to start runoff, 99% of variation can account for this line with 95% confidence level. Correlation coefficient also shows that the reliability of association between observed and predicted data is 99%. For the runoff duration about 90% of variation can account for the best fit line with

Table 7.6 Statistical analysis of hydrograph parameters

Parameters	Symbol	Unit	1- Coefficient of efficiency technique				Standard error
			(F1) =		(F2) =		S
			$\Sigma(\text{predicted-observed})^2$	$\Sigma(\text{observed-mean observed})^2$	Efficiency		
Time to runoff	T_r	min	14219.8	1328.2	0.900		5.979
Time to peak	T_p	min	20560.4	266.7	0.987		5.863
Peak flow rate	Q_p	mm/hr	267.4	40.4	0.990		2.608
Duration of runoff	T_d	min	1227	1811.5	-0.520		9.663
Total runoff	Q_t	mm	25.84	83.809	0.690		1.498
2- Correlation analysis technique:							
Equation	Slope (a_1)		Intercept (a_0)		Correlation coefficient		
	Main value	(Lower limit) _{95%}	(Upper limit) _{95%}	Main value	(Lower limit) _{95%}	(Upper limit) _{95%}	Calculated Tabulated
$y = 0.8311x - 3.546$	0.831	0.702	0.960	-3.546	-11.285	4.192	0.990 0.754
$y = 1.0695x - 5.326$	1.070	0.964	1.175	-5.326	-15.336	4.684	0.996 0.754
$y = 0.954x + 0.479$	0.954	0.544	1.364	0.479	-7.154	8.111	0.995 0.754
$y = 1.243x + 8518$	1.243	0.534	1.952	0.852	-37.870	39.570	0.896 0.754
$y = 1.1736x - 0.32$	1.174	0.753	1.594	-0.320	-4.539	3.900	0.955 0.754

95% confidence level. The reliability of association between observed and predicted runoff duration is also 90 %. Among the hydrograph parameters maximum correlation coefficient and minimum standard error exist between predicted and observed runoff volumes. Conversely, minimum correlation and maximum standard error exist between observed and the predicted duration of runoff. This is because the runoff duration is difference between time to start runoff and time to end runoff. The predicted time to start runoff is smaller than observed time to start runoff for all the experiments (section 7.3.1).

The T-test indicated that the discrepancy between predicted and observed data was not significant in each experiment. This was because the slope of best fit line and the intercept values were not significantly different from unity and zero respectively.

Of particular importance to sprinkler irrigation management is the time when runoff begins, the time it takes to reach the peak, the peak discharge and the volume of runoff. This information could influence the field manager's decision about how much water to apply at one irrigation and the extent to which he might wish to change the cultivation practice to control the runoff. Fortunately there is visually and statistically close relationship between almost all observed and simulated parameters. This means under validation conditions in this study the model simulates these factors successfully.

7.5 Model validation for soil and water conservation techniques

Soil and water conservation techniques are necessary to protect a field against runoff and erosion hazard. These techniques are taken into account by EUROSEM model, but it is necessary to evaluate the model for these techniques. A series of experiments were undertaken in the field for this purpose which will be discussed in this section.

7.5.1 Impact of runoff on soil water distribution along open furrows

Poor distribution of soil water along a longitudinal slope is a marginal effect of runoff under sprinkler irrigation systems. To investigate this phenomena twenty-four hours after running each test, soil samples were taken from the field site and the water contents were measured in the laboratory using gravimetric method. The samples were taken from 0.0 to 300 mm depth repeated at every 3 m distance along the slope. Figure 7.11 demonstrates a few examples of the impact of runoff on soil water distribution along a slope. According to this figure, in some cases soil water content increases from the top to the middle and then reduces from the middle to the bottom of furrows. In some other cases soil water content remains constant along the slope , while the water application rate reduces from the top to the bottom of furrows. Due to nearly constant initial soil water content and reduction of water application rates along a furrow, the soil water distribution was also expected to reduce from the top to the bottom, but it was opposite. Therefore, runoff could be the main reason of increasing soil water content down the slope.

7.5.2 Effect of soil and water conservation techniques on runoff

The soil and water conservation techniques such as micro-basin and pitting on soil and water protection are characterized by roughness ratios along slope (RFR) and across the slope (ASR). These factors can be determined using the relationship described in section 2.3. The RFR is more effective than the ASR on runoff prevention (see section 5.2.5). This is because this factor describes the roughness ratio along the slope where runoff flows. The values of RFR and the ASR of different techniques were already presented in Table 7.2. According to this table the value of RFR for pitting is equal to that of micro-basin. This is because the pitting was built by soil cutting and micro-basins

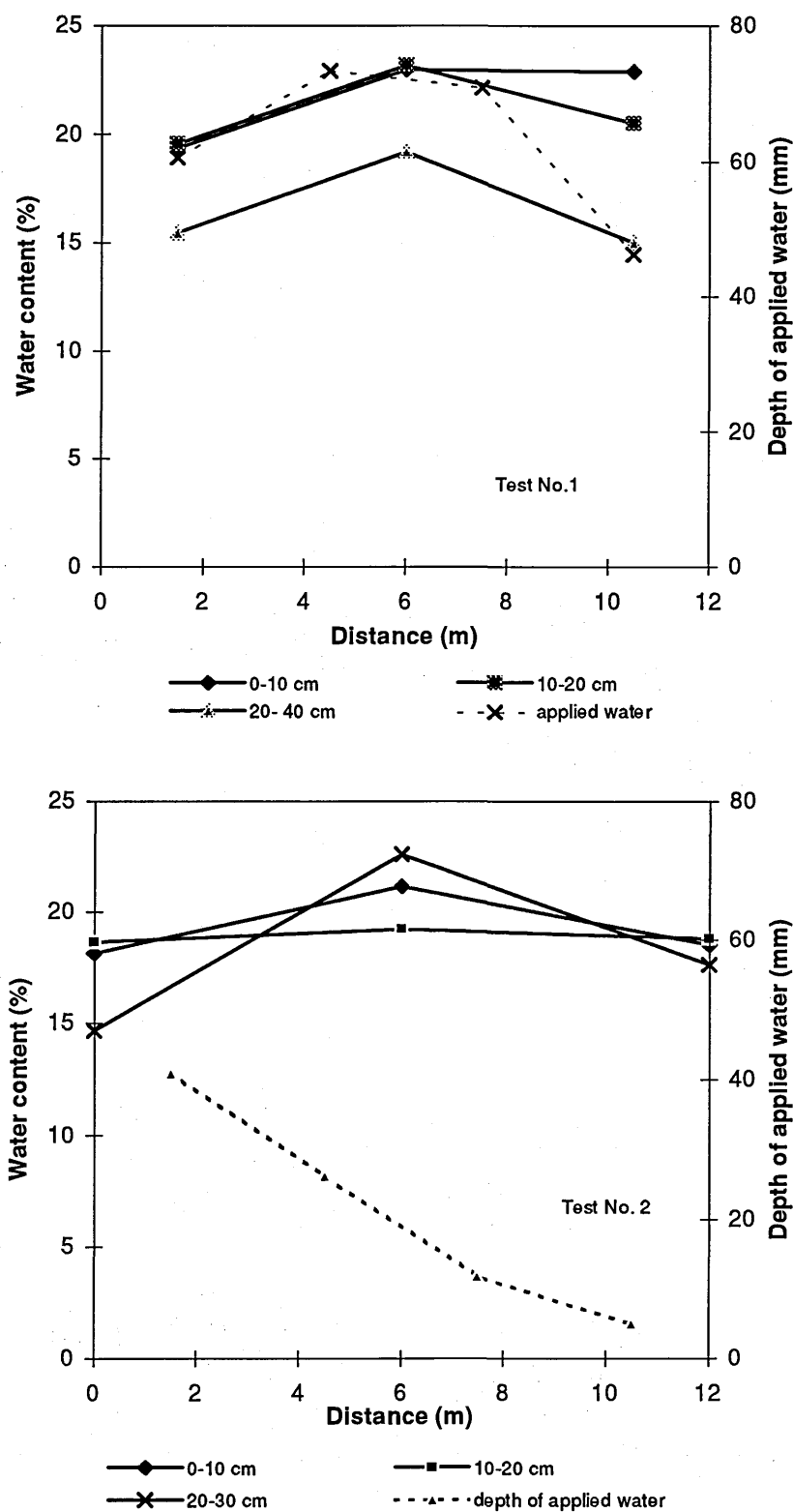


Figure 7.11 Effect of runoff on soil water distribution along a furrow

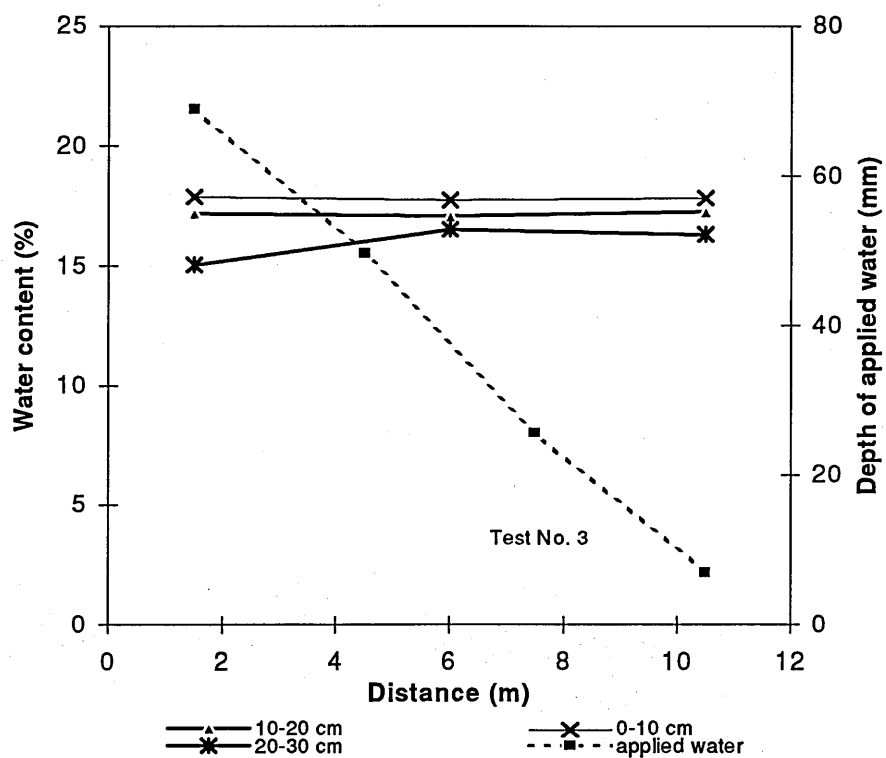
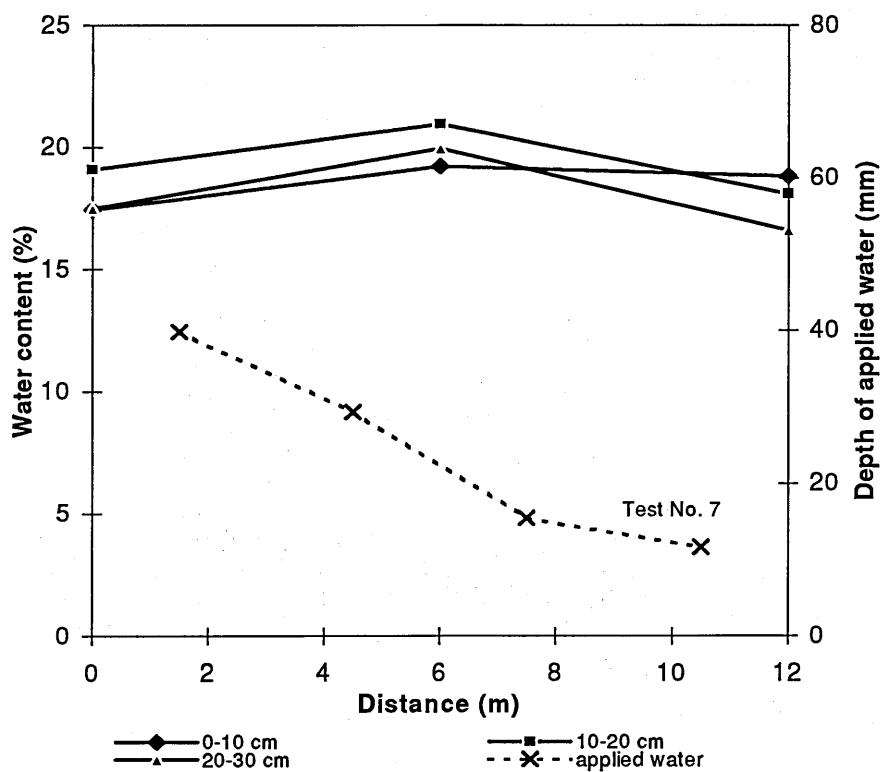


Figure 7.11 Effect of runoff on soil water distribution along a furrow (contd.).

was built by soil filling, so that the cut and fill soil volumes are the same. There is not much difference between the RFR for straw mulching and for free furrow. No runoff observed along a tied furrow (micro-basin) and a furrow with pitting under water application rate of 17 mm/hr and 27.4 mm/hr. The model simulates the effect of the soil and water conservation techniques on runoff prevention very well. From the economical point of view, a decision to create pitting or micro-basin techniques to prevent runoff in field is very important. For example: it is possible to make pitting and tied furrow every other to save time and money.

Although the mulched furrow was free, no runoff observed along it. Straw mulch prevented the direct impact of water drops that could cause soil crust and sealing. Therefore, the saturated hydraulic conductivity of soil would be quite high. On the other hand, the straw mulches create some depression storage on the soil surface that stored water and prevented runoff (see section 2.7.2). These are the reasons why no runoff observed in this technique compared to untied furrows. The model also simulates the behaviour of this technique successfully.

7.6 The effect of soil conservation techniques on soil water distribution

Field tests indicated that the soil and water conservation techniques not only effectively prevented runoff along furrows but also caused nearly uniform distribution of water along them (Figure 7.12). The average uniformity distribution coefficients of soil water contents through soil profile along the free furrows are presented in Table 7.7. A rough comparison between figures shows that the uniformity coefficient in 100 mm of top soil is often higher than in underlying layers. This difference might be due to inadequate time in which wetting front did not reach to lower layers to distribute water into soil profile

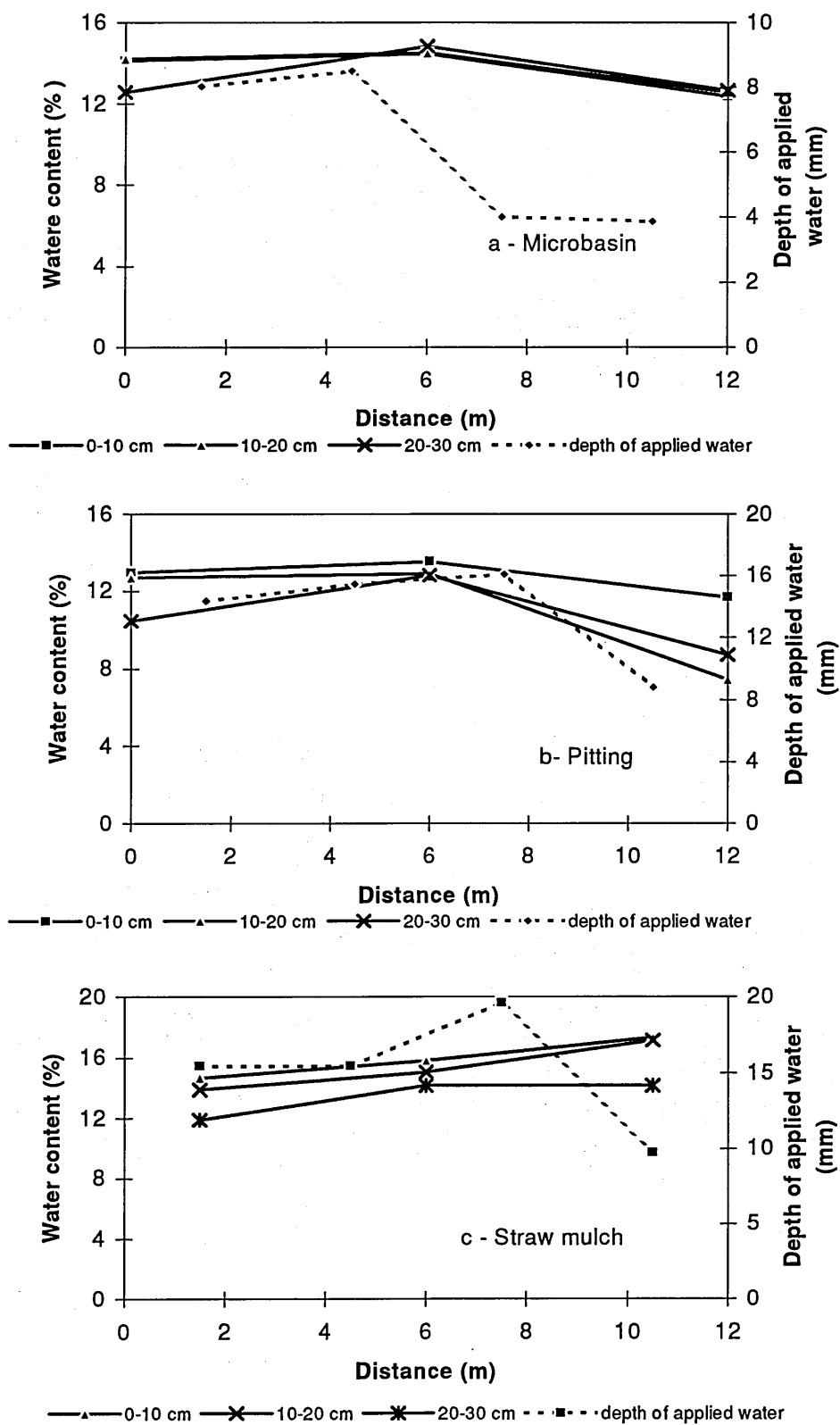


Figure 7.12 The effect of soil and water conservation techniques on uniformity distribution of soil water

Table 7.7 The average uniformity distribution coefficients of soil water content along free furrow

Test / plot	Initial soil water content (%)*	Average uniformity coefficient (%)			Depth of applied water mm
		0-10 cm	10-20 cm	20-30 cm	
Furrow 6/Test 1	9.5	92.7	93.4	89.4	147
Furrow 6/Test 2	29.4	93.5	98.8	84.4	29
Furrow 4/Test 3	18.1	99.6	99.2	96.2	45
Furrow 4/Test 4	23.4	96.0	96.8	95.4	18
basin /Test 7	22.4	96.2	94.5	92.8	28

* soil water content by volume

Table 7.8 The average uniformity distribution coefficients of soil water contents for different soil and water conservation techniques

Technique	Initial soil water content (%)*	Average uniformity coefficient (%)			Depth of applied water mm
		0-10 cm	10-20 cm	20-30 cm	
Micro-basin	17	93.7	94.2	92.6	11
Pitting	14.1	94.6	78.4	86.5	25
Straw mulch	19.5	94.1	92.3	92.5	28

• soil water content by volume

uniformly. The average uniformity distribution coefficients of soil water contents through soil profile along the tied furrows are presented in Table 7.8. According to this table, the uniformity distribution coefficients of soil water content down the slope of a tied furrow (micro-basin) and through the soil profile are high (93.5%) and nearly uniform.

The average distribution uniformity coefficients of water content along the mulched furrow are also high (93%) and nearly uniform through the soil profile, but this seems to be valid for low water application rate. This is

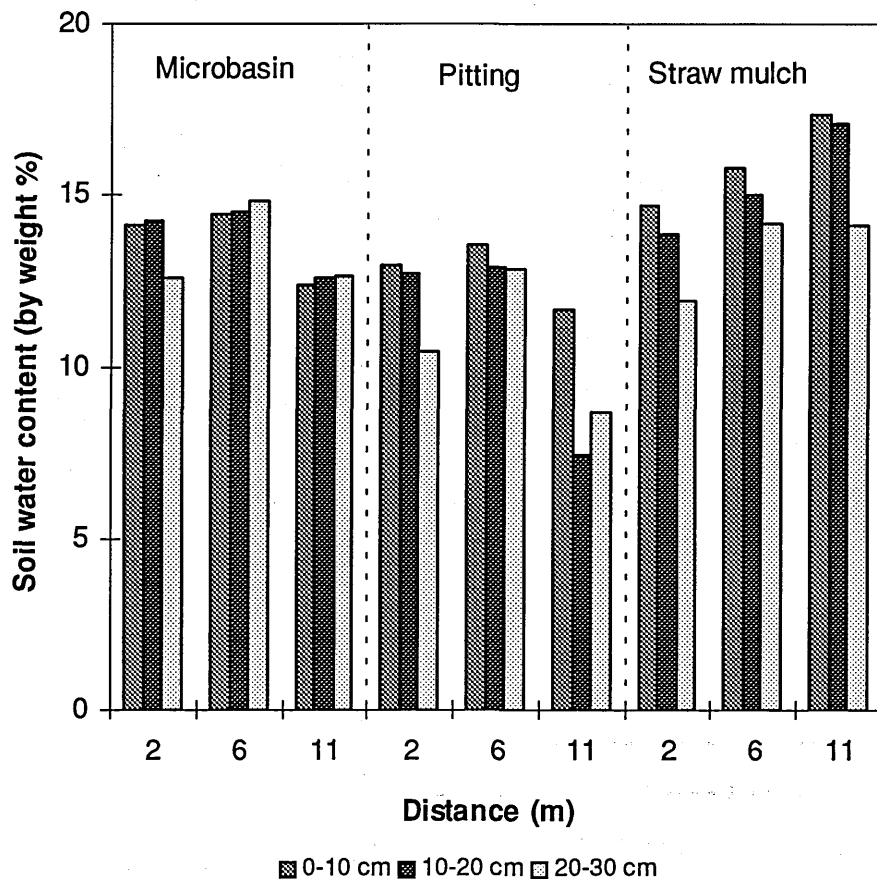


Figure 7.13 The effect of different soil and water conservation techniques on soil water distribution along a furrow.

because, small depression storage is effective at low water application rate and low soil slope. However, when the water application rate exceeds soil infiltration capacity runoff occurs. Therefore, the distribution of soil water content along the furrow with straw mulch will be like a free furrow increasing to down slope. Although the pitting techniques prevent runoff, its effectiveness on average water uniformity distribution along the furrow is higher for the top layer and lower than that of other techniques for underlaying layers. This is because runoff from the sides discharged into the pits and caused a non-uniform water distribution over bed surface. Figure 7.13 demonstrates a comparison between the effect of soil and water conservation techniques on soil water distribution along a furrow.

Overall, the soil and water conservation techniques seem to be effective in agricultural area to prevent runoff and distribute soil water along the slopes. More field work and statistical analysis are required to find the effectiveness of runoff on soil water distribution and crop production.

7.7 Summary

A summary of this discussion is as follows:

- 1- There is good agreement between observed and simulated hydrographs and corresponding parameters (such as time to runoff, time to peak, peak flow rate, the volume of runoff, except runoff duration) for moving sprinkler conditions. Therefore, the KINEROS model can predict runoff from micro-catchments of different cultivation practices (furrow and simple plane) under a moving sprinkler over a wide ranging of operating conditions.
- 2- Runoff causes non-uniformity of soil water distribution along the main slope of micro-catchment and through the soil profile.
- 3- Soil and water conservation techniques not only prevents runoff along the slope, but also results in good uniformity of water distribution along the slope. Among them, tied furrow produced the best uniformity distribution of water followed by mulch and pitting. The EUROSEM model simulates the behaviour of the soil and water conservation techniques successfully.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

8. Conclusions and recommendations

The principal objective of this dissertation was to develop a mathematical model to simulate runoff from micro-catchments under stationary and moving sprinkler systems. Being able to predict runoff under sprinkler irrigation would enable water application rate to be recommended and cultivation practices to be 'designed' rather than guessed on a trial and error basis in order to store surface water and avoid runoff.

The objective was met in two ways:

- 1- A mathematical model was developed for first principles-Overland Flow (OLF)
- 2- An existing model, KINEROS modified to EUROSEM, but designed for overland flow and soil erosion from hydrological watersheds, was applied to micro-catchment conditions for both stationary and moving sprinklers. This model proved to be the most effective and so this was used for further simulation purposes.

So the conclusions are summarised as follows:

8.1 Overland Flow (OLF) model

This model was developed from the same principles as the KINEROS-EUROSEM model, i.e. it was based on the kinematic wave theory. The main differences between this model and the KINEROS-EUROSEM model are less input data is required and it is easier to use. This model takes account of initial soil water content, soil characteristics and water application rate and predicts runoff from a simple plane, a ridge and furrow and a cascade. Laboratory and field validation showed that the model predicts well the shape of the runoff hydrograph. Although it proved useful for some applications, it

was less adaptable for more complex applications such as moving sprinklers. So the limitations for the OLF model are as follows:

- 1- This model cannot take account of all the variations in soil and rainfall characteristics that normally exist in the field. So the model operates like a semi-lumped model, i.e. there is just one average value for some parameters.
- 2- The model cannot directly simulate all the changes in water application depth caused by irrigation machine travel speed, so it cannot simulate runoff from a moving sprinkler.
- 3- Depression storage is not included so this model cannot be used to assess the soil and water conservation techniques in an agricultural area.
- 4- The interception storage also is not included, so the model can only simulate runoff from bare soils, not cultivated areas.

For these reasons, the emphasis of this dissertation changed from further developing this model to an existing one which already had many of these features built in.

8.2 KINEROS-EUROSEM model

This model was developed to assess soil erosion from hydrological watersheds. So after validation it may also be useful to predict soil erosion from agricultural areas. However, the model is limited to larger hydrological watersheds and it has not been tested for micro-catchments under sprinkler irrigation, especially for moving sprinkler systems. For these reasons the model was modified so that it could determine runoff from interconnected small catchments (cascade) under moving as well as stationary sprinklers (similar to a moving rainstorm)

KINEROS-EUROSEM was calibrated for capillary drive and hydraulic conductivity parameters and validated using Leave-Half-Cross validation technique. The model was validated using data collected in laboratory and field tests under stationary and moving sprinkler systems. Laboratory and field tests were undertaken on simple plane and ridge and furrow cultivation to collect the data for validation purposes. At the field site, a line source sprinkler that produces different application rate was used for this purpose.

Visual and statistical techniques were used to compare the predicted runoff hydrographs with observed data. Both methods showed that the model predicts well the shape of the runoff hydrograph but also the key points for practical application. For example, time to start runoff, time to peak, peak flow rate, volume of runoff and time to end which are important when designing a cultivation practice in the field.

8.3 Contribution to the knowledge

The KINEROS-EUROSEM model which had been developed for large hydrological watersheds has been used for the first time to predict surface runoff from simple plane and ridge and furrow micro-catchments under stationary and moving sprinkler irrigation systems. The model has been calibrated and validated using laboratory and field tests. The Model simulates observed runoff hydrographs and corresponding parameters successfully.

The main objective of runoff modelling for sprinkler irrigation systems is to apply the predicted runoff hydrograph and corresponding parameters to irrigation design and management. This is achieved because the model simulated hydrograph parameters, time to start runoff, time to peak runoff, peak flow rate, volume of runoff and time to end successfully and they can be used for this purpose. The time to start runoff is important, because the application time of an irrigation system such as pulse (intermittent) sprinkler

irrigation can be designed so that runoff generation is prevented or reduced. The time to peak is also important, because this can be used as a guide to select the water application time so that no critical situations occur. The peak flow rate is a clue for maximum permissible water application rate to prevent destruction of soil and water constructions. The volume of soil and water conservation structures can be determined by using the total runoff volume. The runoff duration can be used for the selection of furrow or simple plane length to prevent runoff from end of field when there is no soil and water conservation structures. In the last case irrigation machine is not necessary to travel whole length of field, because the bottom of field is designed to irrigate by runoff.

8.4 Recommendations

In order to improve the accuracy of runoff prediction and scope of simulation, further investigations are recommended as follows:

1- Model validation for a moving sprinkler is recommended to be undertaken for different moving irrigators such as rainguns, centre pivot, side move systems and low energy precision application (LEPA) systems. The field experiments should be followed in a zero wind conditions. Otherwise, the model should be modified to simulate the wind speed and direction as well.

2- Further investigations are required to determine the most accurate, easiest and low cost method of measuring the soil infiltration rate for different types of soil texture under sprinkler irrigation. This is a key input parameter to the model and its measurement requires refinement.

3- Further investigations are required to evaluate the use of the model to predict the effects of soil and water conservation techniques on runoff prevention.

4- In this thesis the model was validated for a bare soil. Further investigations are required to validate the model for a cultivated land for different crops.

5- The KINEROS-EUROSEM model is a sophisticated one and needs a lot of input parameters. In order to reduce costs and time investment for collecting the input parameters, the model should be modified to eliminate some of the parameters to which model has very low sensitive.

9. References

- ABO-GHOBAR, H M A (1988) The development of a mathematical model to predict runoff from a micro-catchment under high water application rates. Ph.D. Thesis, Silsoe College, Cranfield University, UK.
- ABO-GHOBAR, H M A (1990) Predicting runoff from a micro-catchment. Journal of Agricultural Engineering, 45, 101-105.
- ADDINK, J W (1975) Runoff potential of spray nozzle and sprinkler centre pivot. ASAE, 75-2056, 8 pp.
- ADRIAN, R C (1952) Measuring water in small channels with flume. Washington Agricultural Experiment Stations, Institute of Agricultural Science, State College of Washington.
- AMIR, I and ALCHANUTIS V (1992) Procedure for prediction and designing moving sprinkler application patterns. Irrigation Science, 13, 93-98.
- BEASLEY, D B, HUGGINS, L F and MONKE E J (1980) A model of watershed planning. Transaction of American Agricultural Engineers, 23, 938-944.
- BENAMI, A and HORE F R (1964) A new irrigation sprinkler distribution coefficient. Transactions of American Society of Agricultural Engineers, 7(1), 157-158.
- BENAMI, A and OFEN, A (1983) Irrigation engineering. Engineering scientific publications, Haifa.
- BEN-HUR, M (1994) Runoff, Erosion and polymer application in moving sprinkler irrigation. Soil Science, Vol. 158, 4, 283-290.
- BEN-HUR, M, PLAUT, Z, LEVY, G L, AGASSI, M and SHAINBERG, I (1995) Surface runoff, uniformity of water distribution and yield of peanut irrigated with moving sprinkler system. Agronomy Journal, 87, 619-613.
- Bernuth, R D V and Gilley, J R (1983) Evaluation of centre pivot application packages considering droplet induced infiltration reduction. ASAE, 83, 2516.
- BETSON, R P (1964) What is watershed runoff? Journal of Geophysical Research, 69 1541-1551.
- BRAKENSIEK, D L (1967a) Finite difference methods. Water Resources Research, 8(3), 858-860.
- BRAKENSIEK, L D (1967b) Kinematic flood routing. Transactions of American Society of Agricultural Engineering, 10(3), 340-343.
- CHAPMAN, T G, DUNIN, F and LANGFORD, K J (1975) Prediction in catchment Hydrology, Overland flow. Australian Academy of science Ltd.
- CHEN, C N and WONG, T S W (1993) Critical rainfall duration for maximum discharge from overland plane. Journal of Hydraulic Engineering Vol. 119, 1040.
- CHOW, V T (1956) Open channel hydraulics. Megraw-Hill Ltd., New York.

- CRESSWELL, H P, SMILES, D S and WILLIAMS, J (1992) Soil structure, soil hydraulic properties and soil water balance. Australian Journal of Soil Research, 30, 265-83.
- DHI, (1985) Introduction to the SHE. Danish Hydraulic Institute, Horsholm, Denmark.
- DANNIEL, M K, FREDERICK, J W and BURROUGHS, E R (1995) Effects of surface roughness and rainfall impact on overland flow. Journal of Hydraulic Engineering, 121, 546-553.
- DONALD, G M (1970) Runoff-rainfall-general. Handbook on the principle of hydrology. Published by the Secretariat, Canadian National Committee for the International Hydrological Decade, Ottawa, Canada.
- ELLIOT, W J, LIEBENOW, A M, LAFLIN, L M and KOHL, K D (1989) A compendium of the soil erodibility data from the WEPP cropland soil filled erodibility experiments 1987 & 1988. NSERL report, 3, the Ohio state University and USDA Agricultural Research Service.
- ENGMAN, E T (1986) Roughness coefficient for routing surface runoff. Journal of Irrigation and Drainage Division, ASCE 112, 39-53.
- EVANS, D and BUOL, W (1968) Micromorphological study of soil crust. Soil Science Society American Journal, 32, 19-22.
- FARDAD, H (1991) Irrigation principles, Vol.1. Tehran University Press, IRAN (Persian Language).
- FETTER, C W (1994) Applied Hydrology. Third edition Magmillan Company Publishing, New York.
- FIRST VOLCANIC INTERNATIONAL SYMPOSIUM (1993) International Water and Irrigation Review. Vol. 13,1, 10 -11.
- FOK, Y S (1985) Derivation of Lewis-Kostiakov intake equation. ASCE, Journal of Irrigation and Drainage, 112(2), 164-171.
- FOSTER, G R, HUGGINS, L F and MEYER, L D (1968) Simulation of overland flow on short field plots. Water Resources Research, 4(6), 1179-1187.
- FOSTER, G L, HUGGINS, L F and MEYER, L D (1984) A laboratory study of rill hydraulic: 1. Velocity relationship. Transaction of American Agricultural Engineers, 27, 790-796.
- FOSTER, G R, LANE, I J, NOWLAN, J D, LAFLIN, J M and YOUNG, R A (1981) Estimating erosion and sediment yield on field-sized area. Transaction of American Agricultural Engineers, 1253-1263.
- FRENCH, R (1985) Open-channel hydraulic. Megraw-Hill Book Company, New York.
- FUKUI, Y, NAKANISHI, K, and OKAMURA, S (1980) Computer evaluation of sprinkler irrigation uniformity. Irrigation Science, 2, 23-32.
- GAYLE, G A and SKAGGS, R W (1978) Surface storage behind cultivated land. Transaction of American Agricultural Engineers, 21(1), pp 101-104, 109.
- GARDNER, W R (1958) Some steady state solution of the unsaturated moisture flow equation with application to evaporation from a water table. Soil science, 85, 228-232.

- GHORBANI, B (1988) The evaluation of local scour depth around bridge piers and selection of the proper method for Fars rivers. (Persian language), MSc thesis, Shiraz University, IRAN.
- GILLEY, J E and KOTTWITZ, E R (1994) Maximum surface storage provided by crop residue. Journal of Irrigation and Drainage Engineering, 120, 2, 440-450.
- GILLEY, J E, FINKNER, S C, NEARING, M A and LANE, L J (1989) Hydraulics of overland flow in USDA- water prediction project, Hill slope profile model documentation. NSERL report No 2 USDA- ARS, National soil erosion research laboratory , West lafayette Indiana.
- GILLEY, J R (1992) Design and management of centre-pivot irrigation systems. Proceeding of international conference on advances in planning, Design and management of irrigation systems as related to sustainable land use. Vol. 1, 347-356.
- GILLEY, J R and MIELKE, L N (1980) Conserving energy with low-pressure centre-pivot. Journal irrigation Drainage Division, American Society Civil Engineering, 106, 49-59.
- GOULT, R J, HOSKINS, R F, MILNER, J A and PRATT, M J (1973) Applicable mathematics. A course for scientists and engineers, Collier-Macmillan Ltd., London.
- GREEN, I R A and STEPHENSON, D (1986) Criteria for comparison of single event models. Hydrological Science Journal, 31, 3, 9, 395-411.
- GREEN, W H and AMPT, G A (1911) Studies in soil physics, the flow of water and air through soils. Journal Agricultural Science (Cambridge), 4, 1-24.
- HUIBERS, F P and STROOSNIJDER (1992) Crop water use efficiency. In: Diemer, G and Slabbers, J, Irrigators and Engineers. Thesis publishers and engineers, Amesterdam, 1992, 259-264.
- HAIRSINE, P B, MORAN, C J and ROSE, C W (1992) Recent development regarding the influence of soil surface characteristics on overland flow and erosion. Australian Journal Soil Research, 30, 249-64.
- HAAN, C T, JOHNSON, H P and BRAKENSIEK, D L (1982) Hydrologic modelling of small watersheds. American Society of Agricultural Engineers, St. Joseph, Michigan.
- HANKS, R J, KELLER, J, RANSSEN, V P and WILSON, G D (1976) Line source sprinkler for continuity variable irrigation crop production studies. ASSS, Vol. 40, 3, 426-430.
- HAROLD, T W and LEWIS, E C (1996) Chain diking effects on runoff and winter wheat production. Agronomy Journal, 88, 541-544.
- HASHEMINIA, S M (1994) Controlling runoff under low pressure center pivot irrigation. Irrigation and Drainage Systems, 8, 25-34.
- HENDERSON, F M (1966) Open channel flow. Collier-Macmillan Ltd., London.
- HILLEL, D, (1980) Application of soil physics. Academic Press, London.

- HIRSCHI, M C and BARFIELD, B J (1988) KYERMO - A physically based research erosion model, Part I. Model development. Transactions of ASAE, Soil and Water Division, 814-820.
- HOLY, M (1980) Erosion and environment (first edition). Pergamon Press, Oxford.
- HOOGMOED, W B and STROOSNIJDER L (1984) Crust formation on sandy soils in the Sahel, I - Rainfall and infiltration. Soil and Tillage Research, 4, 5-24.
- HUGGINS, L F and BURNEY J R (1982) Surface runoff, storage and routing. In: Hann, C T, Johnson, H P and Brakensiek, D L Hydrologic modeling of small watersheds. American Society of Agricultural Engineers, 1982, 169-193.
- HUIBERS, F P and STROOSNIJDER (1992) Crop water use efficiency. Irrigators and Engineers, 259-264.
- ISO 7562-1 (1995) Planning, design and installation of irrigation schemes. Part 3. Guide to irrigation water requirement, International Standard Organisation.
- ISO, 7749-1 (1995) Rotating sprinklers for irrigation equipment. Part 1 Specification for design and operational requirement, International Standard Organisation.
- ISO, 7749-2 (1990) Rotating sprinklers for irrigation equipment. Part 2, Methods of test for uniformity of distribution, International Standard Organisation.
- ISRAESEN, O W and HAUSEN, V E (1962) Irrigation principles and practices Third edition, John Wiley and Sons, New York.
- JIUSHENG, L and HIROSHI, K (1996) Uniformity of water within the root zone under sprinkler irrigation. Journal of Irrigation Engineering and Rural Planning, 30 (2), 89 - 93.
- KAY, M (1983) Sprinkler irrigation equipment and practices. Batsford, London.
- KAY, M (1988) Recent development in surface and overhead irrigation. Silsoe College, Bedford, UK (unpublished).
- KAY, M G and ABO-GHOBAR H (1990) Design method to control runoff from high intensity sprinkler irrigation. Irrigation and Drainage Systems, 4, 109-116.
- KELLER, J (1990) Sprinkle and trickle irrigation. Van Nostrand Reinhold, New York.
- KEMPER, W D (1993) Effect of soil properties on precipitation use efficiency. Irrigation Science, Vol. 14, 2, 65- 68.
- KEULEGAN, G H (1944) Spatially variable discharge over a sloping plane. Transaction of American Geophysical Union, papers hydrology, 956-959.
- KIBLER, D F (1968) A kinematic overland flow model and its optimisation . Ph.D. Thesis, Colorado State University, Fort Collins.
- KIBLER, D F and WOOLHISER, D A (1970) The kinematic cascade hydrological model. Hydrology papers, Colorado state University, Fort Collins, Colorado, 39, 1-4 and 23-25.

- KINCAID, D C, HEERMAN, D F, and KRUSE, E G (1969) Application rates and runoff in centre pivot sprinkler irrigation. Transaction of the ASAE, 12(6), 790-794.
- KIRPICH Z P (1940) Time of concentration of small agricultural watersheds. Engineer Notebook, US Engineer Office, Baltimore.
- KLEMES, V (1986) Operational testing of hydrological simulation models. National Hydrology Research Institute, Environment Canada, Ottawa, Ontario, Canada, K1A OE7. Hydrological Sciences Journal, 31,1,3, 13-24.
- KOSTIAKOV, A N (1932) On the dynamics of the coefficient of water-percolation in soils and on the necessity of studying it from a dynamic point of view for purpose of amelioration. Transaction International Society Soil Science, 6, 17-21.
- LANGFORD, K.J (1975) "Overland flow", Prediction in catchment hydrology. In: Chapman, T G and Dunin, F X, A national symposium on hydrology, Australia Academic of Sciences, 1975, 129-1470.
- LARRY, G J (1988) Principles of farm irrigation system design. John Wiley and Sons, New York.
- LARSON, W E (1979) Soil parameters for evaluating tillage needs and operations. Soil Science Society American Proceeding, 28, 118-122.
- LARSON, C L and MACHMEIER, R E (1968) Peak flow and critical duration for small watersheds. Transaction of American Society of Agricultural Engineers, 11(2), 208-213.
- LETELY, J, VAUX, H V J. and FIENERMAN, E (1984) Optimum water crop application as affected by uniformity water infiltration. Agronomy Journal, 76, 436-441.
- LEVY, G J, LEVIN, J and SHAINBERG, I (1995) Polymer effects on runoff and soil erosion from sodic soils. Irrigation Science, 16, 9-14.
- LIGHTHILL, M H and WHITHAM, G B (1955) On kinematic waves, 1- flood movement in long river. Proceeding Royal Society of London, Ser. A, 229, 281-316.
- LINSLEY, R K, KOHLER, J R M A and PAULHUS, J L H (1988) Hydrology for Engineers. Megraw-Hill Ltd., London.
- LOSIRIKUL, M, NAGAHORI, K and AMAYA, T, (1991) Effect of ridge length and mulching on erosion control - studies of water erosion control practices on reclaimed sloping land (III). Irrigation Engineering and Rural Planning, 20, 7 -17.
- LOSIRIKUL, M, NAGAHORI, K, AMAYA, T and ADACHI, T (1989) Experiments to determine the effectiveness of simple interception ditches in controlling soil erosion - studies on water erosion control practices on reclaimed sloping land (II). Irrigation Engineering and Rural Planning, 17, 21-30.
- MARSHAL, C J (1996) Statistical techniques for model validation. Silsoe College, Bedford, UK (personal communication).
- MECUEN, R H (1973) The role of sensitivity analysis in hydrologic modeling. Journal of hydrology, 18, 37-53.
- MIELKE L N, GILLEY, J R and WILHELM, W W (1992) Low pressure centre-pivot and soil management effect on runoff. Proceeding of

- the international conference on advance planning.cultivation lands. Transaction of the ASAE, 21(1), 101-109.
- MAFF, (1974) Irrigation. Bulletin 138, Ministry of Agriculture, Fisheries and Food, UK.
- MEYNING, W J C and CORDERY, I (1976) Critical duration of rainfall for flood estimation. Water Resources Research, 12(6), 1209-1214.
- MOHAMOUD, Y M (1992) Evaluating Manning's roughness coefficient for tilled soils. Journal of hydrology, 135, 143-156.
- MOORE I D, and LARSON, C L (1979) Estimating micro-relief suffice storage from point data . Transaction of the ASAE, 22, 1073-7.
- MORGAN, D D V and CARR, M K V (1988) Analysis of experiments involving line source sprinkler irrigation, Exp. Agr., Vol. 24, 169-176.
- MORGAN, R P C (1986) Soil erosion and conservation . Longman group limited, UK.
- MORGAN, R P C (1994) The European soil erosion model: An update on its structure and research base. In: Rickson, R.J. (ed.). Conserving Soil Resources: European Perspective. CAB International Walingford, Oxfordshire.
- MORGAN, R P C (1995) Validation of EUROSEM model. Silsoe College, Bedford, UK (personal communication).
- MORGAN, R P C, QUINTON, J N and RICKSON, R J (1992) EUROSEM: Documentation and manual. Silsoe College, Cranfield University, UK.
- MORGAN, R P C, QUINTON, J N and RICKSON, R J (1993) EUROSEM: A user guide. Silsoe College, Cranfield University, UK.
- MURUGABOOPATH, C (1987) Calibration of sprinkler to simulate tropical rainfall. Irrigation Engineering and Rural Planning, 12, 41-48.
- MUSHARIE, A N (1993) Optimization of hose reel raingun irrigation systems in wind: Simulation of the effect of trajectory angle, sector angle, sector position and lane spacing on water distribution and crop yield. Ph.D. thesis, Silsoe College, UK.
- MWENDERA, E J and FEYEN, J (1992) Estimation of depression storage and Manning's resistance coefficient from random roughness measurements. Geoderma, 52, 235-250.
- MWENDERA, E J and FEYEN, J (1993) Predicting tillage effects on infiltration. Soil Science, Vol. 155, 3, 229-235.
- NASH, J E and SUTCLIFFE, J V (1970) River flow forecasting through conceptual models, Part 1- a discussion of principles. Department of engineering, University College, Galway and Institute of Hydrology, UK, Journal of Hydrology, 10, 282-290.
- NEARING, M A, FOSTER G R, LANE, L J, and FINCKNER, S C (1989) A process-based soil erosion model for USDA-Water Erosion Prediction Project Technology. Transaction of American Society of Agricultural Engineers, 32, 1587-1593.
- O'DONNELL, T (1966) Computer evaluation of catchment behaviour and parameter significant in flood hydrology, I.C.E. Symposium, River Flood Hydrology, 103-113.
- OLIVERIA, C A S, HANKS, R J and SHANI, U (1987) Infiltration and runoff as

- affected by pitting, mulching and sprinkler irrigation. Irrigation Science, 8, 49-68.
- OTTO, J H (1989) Evaluation the traveling trickle centre-pivot. ICID Bulletin, Vol. 38,1, 13-20.
- PAIR, C H (1968) Water distribution under sprinkler irrigation. Transaction of American Society of Agricultural Engineers, 11(5), 648-651.
- PARTY, G G and MARINO, M A (1983) Nonlinear runoff modelling: parameter identification. Journal of Hydraulic Division, ASAE, 865-880.
- PHILIP, J R, (1969) Theory of infiltration. Adv. Hydrosc., 5, 215-290.
- POESEN, J W A (1992) Mechanisms of overland flow generation and sediment production on loamy and sandy soils with and without rock fragments. In: Parsons, A J and Abrahams, A D, Overland flow: hydraulics and erosion mechanics. UCL, London Press, 275-305.
- PRESST, A J (1983) Soil management and water use of potatoes. Ph.D. thesis, Silsoe College, UK.
- QUINTON, J N (1994a) The validation of physically-based erosion models with particular references to EUROSEM. Ph.D. thesis, Silsoe College, UK.
- QUINTON, J N (1994b) Validation of physically based erosion models with particular reference to EUROSEM. In: Rickson, R.J. (ed.). Conserving Soil Resources: European Perspective. CAB International Walingford, Oxfordshire.
- REYNOLDS, W D and ELRICK, D E (1990) Ponded infiltration from a single ring: I. Analysis of steady flow; Soil Science Society of America Journal, Vol. 54, 5, , 1233-1240.
- RICHARD, P J and WEATHERHEAD, K H (1993) Prediction of raingun application patterns in windy conditions. Journal of agricultural research, 54, 281-291.
- RICKSON, R J (1994) Potential application of the European soil erosion model (EUROSEM) for the evaluating soil conservation measures. In: Rickson, R.J. (ed.), Conserving Soil Resources: European Perspective, CAB International Walingford, Oxfordshire.
- ROO, A P J and WALLING, D E (1994) Validation the answers soil erosion model using 137Cs. In: Rickson, R.J. (ed.). Conserving Soil Resources: European Perspective, CAB International Walingford, Oxfordshire, UK.
- SCS (1961) National engineering handbook, Irrigation section, sprinkler irrigation. US Department of Agriculture, Soil Conservation Services.
- SHULL, H and DYLLA, A S (1976) Travelling gun application uniformity in high winds. Transactions of American Society of Agricultural Engineers, 19(2), 435-258.
- SMITH, R E and PARLANGE J Y (1978) A parameter-efficient hydrologic infiltration model. Water Resources Research, 14, 533-538.

- SMITH, R E and WOOLHISER, D A (1971) Mathematical simulation of infiltration watersheds. Hydrology papers, Colorado state University, 10-13.
- SMITH, R E, GOODRICH, D C and QUINTON, J N, (1995) Dynamic, distributed simulation of watershed erosion: The KINEROS2 and EUROSEM models. Journal of Soil and Water Conservation, 50 (5), 517-520.
- SMITH, R E (1983) Flux infiltration theory for use in watershed hydrology. In: Proceeding of the national conference on advances in infiltration, American Society of Agricultural Engineering, St. Joseph, MI, 313-323.
- SMITH, R E (1997) EUROSEM: Model calibration (personal communication)
- SOARES, A A, WILLARDSON, L S and KELLER, J (1991) Surface-slope effects on sprinkler uniformity. Journal of Irrigation and Drainage Engineering, 117, 870-879.
- SITS, (1983) Irrigation technical manual engineering data. Staff of irrigation technical services under the direction of A C "Chet" Sarsfield.
- STEPHENSON, D and MEADOWS, M E (1986) Kinematic hydrology and modelling. Elsevier, Amsterdam, The Netherland.
- TAKASAO, T and, TAKARA, K (1988) Evaluation of rainfall- runoff models from the stochastic viewpoint. Journal of Hydrology, 102, 381-406.
- THEO, K.E.M. (1992) Water use efficiency. In: DIEMER, G and SLABBERS, J Irrigators and Engineers. Thesis publishers, Amsterdam, 1992, 93-97.
- VAN VUREN, G H (1992) Irrigation efficiency coefficient. In: DIEMER, G and SLABBERS, J, Irrigators and Engineers. Thesis publishers, Amsterdam, 1992, 97-103.
- WEYMAN, D R (1975) Runoff process and stream flow modeling. Theory and practice in Geography, Oxford University Press, Oxford, UK.
- WHITE, I and SULLY, M J (1987) Macroscopic and microscopic capillary length and time scales from field infiltration. Water Resources Research, 23, 1514-1522.
- WILCOX, J C and SWAILES, G E (1947) Uniformity of water distribution by some under tree orchard sprinklers. Scientific Agriculture, 27(11), 565-583.
- WILLARDSON, L S, OOSLERHAIS, D M and JOHNSON, D A (1987) Sprinkler selection for line source irrigation system. irrigation science, 8, 56-76.
- WILSON, E M (1978) Engineering Hydrology. Macmillan Ltd., London.
- WITHERS, B and STANLEY, V (1985) Irrigation: design and practices. Batsford, London.
- WOLTERS, W B and EERISAVLGEVIC, G K (1991) Patterns and trends in application efficiency. ICID bulletin, Vol. 40, 2.
- WOODING, R A (1965) A hydraulic model for the catchmnet stream problem. I. Kinematic wave theory. Journal of Hydrology, 3(3), 254-267.

- WOOLHISER, D A and GOODRICH D C (1988) Effect of storm rainfall intensity patterns on surface runoff. Journal of hydrology, 102, 335-354.
- WOOLHISER, D A and LIGGETT, J A (1967) Unsteady, one dimensional flow over a plane - the rising hydrograph. Water Resources Research, 3 (3), 753-771.
- WOOLHISER, D A, SMITH, R E and GOODRICH, D C (1990) KINEROS. A kinematic runoff and erosion model: Documentation and user manual. United State Department of Agriculture.
- YAO-HUANG, W, YEVEJEVICH, V and WOOLHISER, D A (1978) Effects of surface roughness and its spatial distribution on runoff hydrographs. Hydrology papers, Colorado State University, 7-9.
- YAXIN, C and GUANGYUN, N (1993) Evaluation of irrigation efficiency and water saving strategy for Hetao, China. ICID Bulletin, Vol. 42, 2, 11-21.
- YOUNGS, E G (1968) An estimation of sorptivity for infiltration studies from moisture moment consideration. Soil Science, 106, 157-163.
- YOUNGS, E G (1991) Infiltration measurement - A review. Hydrological processes, 5, 309 -320.
- YOUNGS, E G (1996) Estimation of capillary drive using 'time to ponding method'. Silsoe College, Bedford, UK, (personal communication).
- ZHAO, B, YEOU-KOUNG, T, KEH-CHIA, Y and JINN-CHUANG, Y (1995) Statistical validation methods: Application to unit hydrographs. Journal of Hydraulic, Vol. 121, 8, 618-624.
- ZIMMERMAN, J D (1966) Sprinkling Irrigation. Consulting irrigation engineers, Wiley and Sons Ltd., UK.

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Appendix A.1 A computer program for Overland flow (OLF) model

A computer program was written in Quick Basic language for the solution of the model developed in chapter 3 to predict surface runoff from a simple plane and ridge and furrow cultivation under sprinkler irrigation. The model based on kinematic wave theory uses the four-point implicit numerical method and a solution is obtained by Newton-Raphson's approach. The model adapts soil and water parameter values of a simple plane or both sides and bed of a ridge and furrow micro-catchment and predicts runoff. The program includes three main subroutines, runoff from simple plane (furrow bed), runoff from sides of furrow and a cascade.

1- List of program symbols

h = runoff depth (m)

q = runoff discharge per unit width (m^2/hr)

h_s = runoff depth for furrow sides

q_s = runoff discharge per unit width of sides

TT = time from the beginning of irrigation (min)

ΔT = time increment (min)

θ_{tab} = the percentage of soil water content (%)

D_i = the initial depth of soil water content (mm)

T_{New} = the time infiltration starts (min)

D_b = the bed distance from upstream (m)

Δx_b = distance increment (m)

x_b = the point number along the slope

Q_r = excess rainfall (mm/hr)

h_{e4} = depth of runoff flow at the end of plane (m)

h_1 = depth of runoff at the first grid point

q_2 = discharge of runoff at the second grid

Appendix A.1 (contd.)

Waterapptime = water application time

Fh = the kinematic wave equation

FFh = the first derivation of kinematic wave equation

The other symbols are explained in the program context

```
CLS : CLEAR
```

```
DEFDBL D, L
```

```
DIM h(400, 2), q(400, 2), hs(100, 2), qs(100, 2)
```

```
'-----Main Programm-----
```

```
b$ = "#####.##   ###.##   ###.###   ###.###   ###.##"
```

```
main:
```

```
PRINT : PRINT : PRINT
```

```
INPUT "      Please Enter b for Plane and s for Ridge and Furrow"; aaaa$
```

```
SELECT CASE aaaa$
```

```
    CASE "b"
```

```
        GOSUB inputb
```

```
        GOSUB outputb
```

```
    CASE "s"
```

```
        GOSUB inputb
```

```
        GOSUB inputs
```

```
        GOSUB outputb
```

```
        GOSUB outputs
```

```
        TT = TT + DeltaT
```

```
        m = 5 / 3
```

```
        GOSUB Side
```

```
        TT = 0
```

```
    CASE ELSE
```

```
        PRINT "      Please Enter Only b or s"
```

```
        GOTO main
```

```
END SELECT
```

Appendix A.1 (contd.)

PRINT #1, "Time (min), Rainfall(mm/hr), Depth (mm), q (m²/h) , Q (mm/h)"

BBb\$ = " 0.00 ###.## 0.0 0.0 0.0"

PRINT #1, USING BBb\$; R

b\$ = "#####.## ###.## ###.### ###.### ###.##"

TT = TT + DeltaT

Di = Thetab * 100

IF ab <> 0 THEN TNew = (Di * (bb + 1) / ab) ^ (1 / (bb + 1))

m = 5 / 3

Start:

Db = Deltaxb + Db

IF Db > Lb THEN

QQQ = q(xb, 2) * 1000 * Wb / (Lb * (Wb + 2 * Ls))

PRINT #1, USING b\$; TT; R; h(xb, 2); q(xb, 2); QQQ

IF (TT > Waterapptime AND QQQ < .1) THEN END

'-----saving Last Data-----'

FOR I = 1 TO (Lb / Deltaxb)

q(I, 1) = q(I, 2): h(I, 1) = h(I, 2)

NEXT I

TT = TT + DeltaT

xb = 0: Db = Deltaxb

IF aaaa\$ = "s" THEN GOSUB Side

END IF

xb = xb + 1

Alfa = 1 / nb * Sb ^ .5

AA = 2 * DeltaT * Alfa: BBb = Deltaxb

Qr = R - ab * (1 / (TT + TNew) ^ (-bb)): Qr = Qr / 1000

IF Qr < 0 THEN

Appendix A.1 (contd.)

Qr = 0

'he4 = 0:GOTO 10

END IF

IF aaaa\$ = "s" THEN Qr = Qr + 2 * qs / Wb

h1 = h(xb - 1, 1): h2 = h(xb - 1, 2): h3 = h(xb, 1)

q2 = q(xb - 1, 2)

IF TT > Waterapptime THEN R = 0

qq = q2

hh = h1 - h2 + h3

'===== Newton Raphson Method =====

PP = 2 * DeltaT * Deltaxb * Qr + Deltaxb * hh + 2 * DeltaT * qq

Fh = .01

DO UNTIL ABS(Fh - 0) < .001

h4 = he4

Fh = AA * h4 ^ m + BBb * h4 - PP

FFh = AA * m * h4 ^ (m - 1) + BBb

he4 = h4 - Fh / FFh

LOOP

10

h(xb, 2) = he4

q(xb, 2) = 1 / nb * Sb ^ (.5) * he4 ^ (5 / 3)

GOTO Start

'-----Subroutine for Plane(Bed) input data -----

inputb:

CLS

PRINT : PRINT : PRINT

PRINT " PLEASE ENTER THE BED PARAMETERS:"

INPUT " The Length (m)..... "; Lb

Appendix A.1 (contd.)

```

INPUT "      The Width (m).....      "; Wb
INPUT "      Application Rate (mm/hr).....      "; R
INPUT "      Longitudinal Slope .....      "; Sb
INPUT "      Manning's Coefficient (metric) "; nb
INPUT "      The Time Increment (min)....."; DeltaT
INPUT "      The Distance Increment (m)....."; Deltaxb
INPUT "      Infiltration Coefficient a (at^b)..      "; ab
INPUT "      Infiltration Coefficient b (at^b).      "; bb
INPUT "      Water Application Time (min)....."; Waterapptime
INPUT "      Initial Moisture Content (Volumetric)"; Thetab
PRINT : PRINT
INPUT "      Do you like to change the data?(Y/N)"; chan$
IF (chan$ = "Y" OR chan$ = "y") THEN CLS : GOTO inputb
CLS
RETURN

'-----Subroutine for Side input data -----
inputs:
Ws = Deltaxb
PRINT : PRINT : PRINT
PRINT "  PLEASE ENTER : "
INPUT "      The Side Length (m).....      .."; Ls
INPUT "      Side Slope .....      ..."; Ss
INPUT "      The Side Manning's Coefficient (metric).      "; ns
INPUT "      The Side Distance Increment (m).....      .."; Deltaxs
INPUT "      The Side Infiltration Coefficient a (at^b).      "; as1
INPUT "      The Side Infiltration Coefficient b (at^b)..      "; bs
INPUT "      Initial Moisture Content of Side (Volumetric)"; Thetas
PRINT : PRINT
INPUT "      Do you like to change the data?(Y/N)"; chan$

```

Appendix A.1 (contd.)

IF (chan\$ = "Y" OR chan\$ = "y") THEN CLS : GOTO inputs

CLS

RETURN

'-----Subroutine for output of Plane -----

outputb:

PRINT : INPUT " Name of output File"; a\$

OPEN a\$ FOR OUTPUT AS #1

PRINT #1, " The Length (m) = "; Lb

PRINT #1, " The Width (m) = "; Wb

PRINT #1, " Application Rate (mm/hour) = "; R

PRINT #1, " Longitudinal Slope = "; Sb

PRINT #1, " The Manning's Coefficient (metric) = "; nb

PRINT #1, " The Time Increment (min) = "; DeltaT

PRINT #1, " The Distance Increment (m) = "; Deltaxb

PRINT #1, " Infiltration Coefficient a (a^b) = "; ab

PRINT #1, " Infiltration Coefficient b (a^b) = "; bb

PRINT #1, " Water Application Time (min) = "; Waterapptime

PRINT #1, " Initial Moisture Content (Volumetric) = "; Thetab

RETURN

'-----Subroutine for output data of side-----

outputs:

PRINT #1, " The Side Length (m) = "; Ls

PRINT #1, " The Side Width (m) = "; Ws

PRINT #1, " The Side Slope = "; Ss

PRINT #1, " The Side Manning's Coefficient (metric) = "; ns

PRINT #1, " The Side Distance Increment (m) = "; Deltaxs

PRINT #1, " The Side Infiltration Coefficient a (a^b) = "; as1

PRINT #1, " The Side Infiltration Coefficient b (a^b) = "; bs

PRINT #1, " Initial Moisture Content of Side (Volumetric) = "; Thetas

Appendix A.1 (contd.)

RETURN

'-----Subroutine for runoff from Sides-----'

Side:

Dis = Thetas * 100

IF as1 <> 0 THEN TNews = (Di * (bs + 1) / as1) ^ (1 / (bs + 1))

qs = 0

REStart:

Ds = Deltaxs + Ds

IF Ds > Ls THEN

FOR I = 1 TO (Ls / Deltaxs)

qs(I, 1) = qs(I, 2): hs(I, 1) = hs(I, 2)

NEXT I

qs = qs(xs, 2)

xs = 0: Ds = 0

RETURN

END IF

xs = xs + 1

Alfa = 1 / ns * Ss ^ .5

AAs = 2 * DeltaT * Alfa: BBs = Deltaxs

Qrs = R - as1 * (1 / (TT + TNews) ^ (-bs)): Qrs = Qrs / 1000

IF Qrs < 0 THEN

Qrs = 0: he4 = 0

GOTO 100

END IF

h1 = hs(xs - 1, 1): h2 = hs(xs - 1, 2): h3 = hs(xs, 1)

q2 = qs(xs - 1, 2)

IF TT > Waterapptime THEN R = 0

Appendix A.1 (contd.)

qq = q2

hh = h1 - h2 + h3

'===== Newton Raphson Method =====

PPs = 2 * DeltaT * Deltaxs * Qrs + Deltaxs * hh + 2 * DeltaT * qq

Fh = .01

DO UNTIL ABS(Fh - 0) < .001

h4 = he4

Fh = AAs * h4 ^ m + BBs * h4 - PPs

FFh = AAs * m * h4 ^ (m - 1) + BBs

he4 = h4 - Fh / FFh

LOOP

100

hs(xs, 2) = he4

qs(xs, 2) = 1 / ns * Ss ^ (.5) * he4 ^ (5 / 3)

GOTO

RESTART

"A program for a cascade"

CLS : CLEAR

DEFDBL D, L

DIM h(500, 2), q(500, 2)

main:

PRINT : PRINT : PRINT

INPUT " Please Enter 1 for Plane and 2 for Ridge and Furrow"; aaaa

SELECT CASE aaaa

'-----Element 1 (Plane 1) -----

CASE 1

repeat1:

Appendix A.1 (contd.)

CLS

PRINT : PRINT : PRINT

PRINT " PLEASE ENTER :"

INPUT " The Length (m)....."; L1

INPUT " The Width (m)....."; W1

INPUT " Application Rate (mm/hour)....."; R

INPUT " Longitudinal Slope"; S1

INPUT " The Manning's Coefficient (metric)."; n1

INPUT " The Time Increment (min)....."; DeltaT

INPUT " The Distance Increment (m)....."; Deltax1

INPUT " Infiltration Coefficient a (at^b).."; a1

INPUT " Infiltration Coefficient b (at^b).."; b1

INPUT " Water Application Time (min)....."; Waterapptime

INPUT " Initial Moisture Content (Volumetric);Theta1

PRINT : PRINT

INPUT " Do you like to change the data?(Y/N)"; chan\$

IF (chan\$ = "Y" OR chan\$ = "y") THEN GOTO repeat1

L1 = : W1 = : R = : S1 = : n1 = : DeltaT =

: a1 = : b1 =

Waterapptime = : Theta1 =

L2 = 0: W2 = W1: S2 = S1: n2 = n1: a2 = a1: b2 = b2: Theta2 = Theta1

'-----Element 2 (Plane 2)-----

CASE 2

repeat2:

CLS

PRINT : PRINT : PRINT

PRINT " PLEASE ENTER :"

Appendix A.1 (contd.)

```

INPUT "      The Side Length (m)..... "; L1
INPUT "      The Side Width (m)..... "; W1
INPUT "      The Bed Length (m)..... "; L2
INPUT "      The Bed Width (m)..... "; W2
INPUT "      Application Rate (mm/hour)....."; R
INPUT "      The Side Slope ..... "; S1
INPUT "      The Side Manning's Coefficient (metric)."; n1
INPUT "      The Bed Slope ....."; S2
INPUT "      The Bed Manning's Coefficient (metric)."; n2
INPUT "      The Time Increment (min)....."; DeltaT
INPUT "      The Side Distance Increment (m)....."; Deltax1
INPUT "      The Bed Distance Increment (m)....."; Deltax2
INPUT "      The Side Infiltration Coefficient a (at^b).."; a1
INPUT "      The Side Infiltration Coefficient b (at^b).."; b1
INPUT "      The Bed Infiltration Coefficient a (at^b).."; a2
INPUT "      The Bed Infiltration Coefficient b (at^b).."; b2
INPUT "      Water Application Time (min)....."; Waterapptime
INPUT "      Initial Moisture Content of Side (Volumetric)"; Theta1
INPUT "      Initial Moisture Content of Bed (Volumetric)"; Theta2
PRINT : PRINT
INPUT "      Do you like to change the data?(Y/N)"; chan$
IF (chan$ = "Y" OR chan$ = "y") THEN GOTO repeat2
L1 = : W1 = : R = : S1 = : n1 = : DeltaT = : a1 = : b1 =
Waterapptime = : Theta1 =

L2 = : W2 = : S2 = : n2 = : a2 = : b2 = : Theta2 =

CASE ELSE
PRINT "      Please Enter Only 1 or 2"
GOTO main

```

Appendix A.1 (contd.)

END SELECT

TT = DeltaT: L = L1 + L2

PRINT : INPUT " Name of output File"; a\$

OPEN a\$ FOR OUTPUT AS #1

SELECT CASE aaaa

CASE 1

PRINT #1, " The Length (m) = "; L1

PRINT #1, " The Width (m) = "; W1

PRINT #1, " Application Rate (mm/hour) = "; R

PRINT #1, " Longitudinal Slope = "; S1

PRINT #1, " The Manning's Coefficient (metric) = "; n1

PRINT #1, " The Time Increment (min) = "; DeltaT

PRINT #1, " The Distance Increment (m) = "; Deltax

PRINT #1, " Infiltration Coefficient a (a^b) = "; a1

PRINT #1, " Infiltration Coefficient b (a^b) = "; b1

PRINT #1, " Water Application Time (min) = "; Waterapptime

PRINT #1, " Initial Moisture Content (Volumetric) = "; Theta1

CASE 2

PRINT #1, " The Side Length (m) = "; L1

PRINT #1, " The Side Width (m) = "; W1

PRINT #1, " The Bed Length (m) = "; L2

PRINT #1, " The Bed Width (m) = "; W2

PRINT #1, " Application Rate (mm/hour) = "; R

PRINT #1, " The Side Slope = "; S1

PRINT #1, " The Side Manning's Coefficient (metric) = "; n1

PRINT #1, " The Bed Slope = "; S2

PRINT #1, " The Bed Manning's Coefficient (metric) = "; n2

PRINT #1, " The Time Increment (min) = "; DeltaT

PRINT #1, " The Side Distance Increment (m) = "; Deltax1

Appendix A.1 (contd.)

```

PRINT #1, " The Bed Distance Increment (m) = "; Deltax2
PRINT #1, " The Side Infiltration Coefficient a (at^b) = "; a1
PRINT #1, " The Side Infiltration Coefficient b (at^b) = "; b1
PRINT #1, " The Bed Infiltration Coefficient a (at^b) = "; a2
PRINT #1, " The Bed Infiltration Coefficient b (at^b) = "; b2
PRINT #1, " Water Application Time (min) = "; Waterapptime
PRINT #1, " Initial Moisture Content of Side (Volumetric) = "; Theta1
PRINT #1, " Initial Moisture Content of Bed (Volumetric) = "; Theta2
END SELECT
PRINT #1, "Time (min), Rainfall(mm/hr), Depth (mm),  q (m^2/h) ,  Q
(mm/h)"
BBB$ = " 0.00   ###.##      0.0      0.0      0.0"
PRINT #1, USING BBB$; R
b$ = "#####.##   ###.##   ###.###   ###.###   ###.##"

```

Start:

```
IF D <= L1 THEN
```

```
Case$ = "First"
```

```
Deltax = Deltax1
```

```
ELSE
```

```
Deltax = Deltax2
```

```
END IF
```

```
D = Deltax + D: x = x + 1
```

```
IF D > L THEN
```

```
TT = TT + DeltaT
```

```
x = 1: D = Deltax
```

```
FOR I = 1 TO (L / Deltax)
```

```
q = q(l, 1) = q(l, 2): h(l, 1) = h(l, 2)
```


Appendix A.1 (contd.)

NEXT I

END IF

SELECT CASE Case\$

CASE "First"

 $Di = \text{Theta1} * 100$ $\text{IF } a1 \neq 0 \text{ THEN } T_{\text{New}} = (Di * (b1 + 1) / a1)^{(1 / (b1 + 1))}$ $\text{Alfa} = 1 / n1 * S1^{.5}; m = 5 / 3$ $AA = 2 * \Delta T * \text{Alfa}; BB = \Delta t_{ax}$ $Q_r = R - a1 * (1 / (TT + T_{\text{New}})^{-b1}); Q_r = Q_r / 1000$ IF $Q_r < 0$ THEN $Q_r = 0; h_{e4} = 0$

GOTO 10

END IF

CASE ELSE

 $Di = \text{Theta2} * 100$ $\text{IF } a2 \neq 0 \text{ THEN } T_{\text{New}} = (Di * (b2 + 1) / a2)^{(1 / (b2 + 1))}$ $\text{Alfa} = 1 / n2 * S2^{.5}; m = 5 / 3$ $AA = 2 * \Delta T * \text{Alfa}; BB = \Delta t_{ax}$ $Q_r = R - a2 * (1 / (TT + T_{\text{New}})^{-b2}); Q_r = Q_r / 1000$ IF $Q_r < 0$ THEN $Q_r = 0; h_{e4} = 0$

GOTO 10

END IF

END SELECT

 $h1 = h(x - 1, 1); h2 = h(x - 1, 2); h3 = h(x, 1)$ $q2 = q(x - 1, 2)$ IF $TT > \text{Waterapptime}$ THEN $R = 0$ $qq = q2$ $hh = h1 - h2 + h3$

Appendix A.1 (contd.)

'===== Newton Raphson Method =====

$PP = 2 * \Delta T * \Delta x * Q_r + \Delta x * hh + 2 * \Delta T * qq$

$F_h = .01$

DO UNTIL $ABS(F_h - 0) < .001$

$h_4 = h_{e4}$

$F_h = AA * h_4^m + BB * h_4 - PP$

$FF_h = AA * m * h_4^{(m-1)} + BB$

$h_{e4} = h_4 - F_h / FF_h$

LOOP

10 $h(x, 2) = h_{e4}$

 SELECT CASE Case\$

 CASE "First"

$q(x, 2) = 1 / n_1 * S_1^{(.5)} * h_{e4}^{(5/3)}$

 CASE ELSE

$q(x, 2) = 1 / n_2 * S_2^{(.5)} * h_{e4}^{(5/3)}$

 END SELECT

IF $ABS(D - L) < .0001$ THEN PRINT #1, USING b\$; TT; R; $h(x, 2)$; $q(x, 2)$; $q(x, 2) * 1000 * W_2 / (L_1 * W_1 + L_2 * W_2)$

'IF $ABS(D - L) < .0001$ THEN PRINT USING b\$; TT; R; $h(x, 2)$; $q(x, 2)$; $q(x, 2) * 1000 * W_2 / (L_1 * W_1 + L_2 * W_2)$

IF $(TT > \text{Waterapptime AND } ABS(q(x, 2) - 0) < .00001)$ THEN

PRINT #1, USING b\$; TT; R; $h(x, 2)$; $q(x, 2)$; $q(x, 2) * 1000 * W_2 / (L_1 * W_1 + L_2 * W_2)$

END

END IF

GOTO Start

Appendix A.1 (contd.)

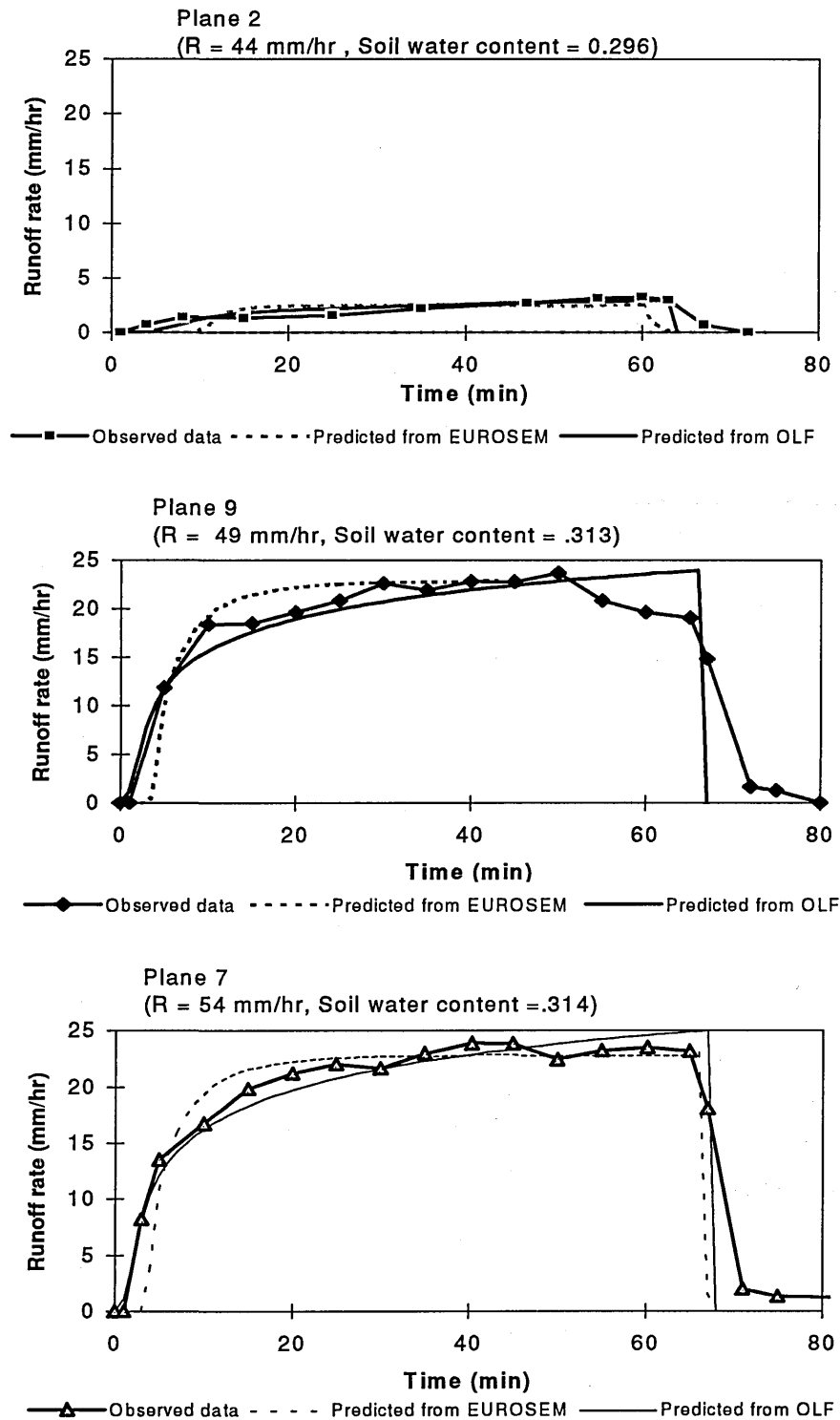


Figure A.1 Comparison of predicted runoff from EUROSEM and OLF models with observed data

Appendix A.1 (contd.)

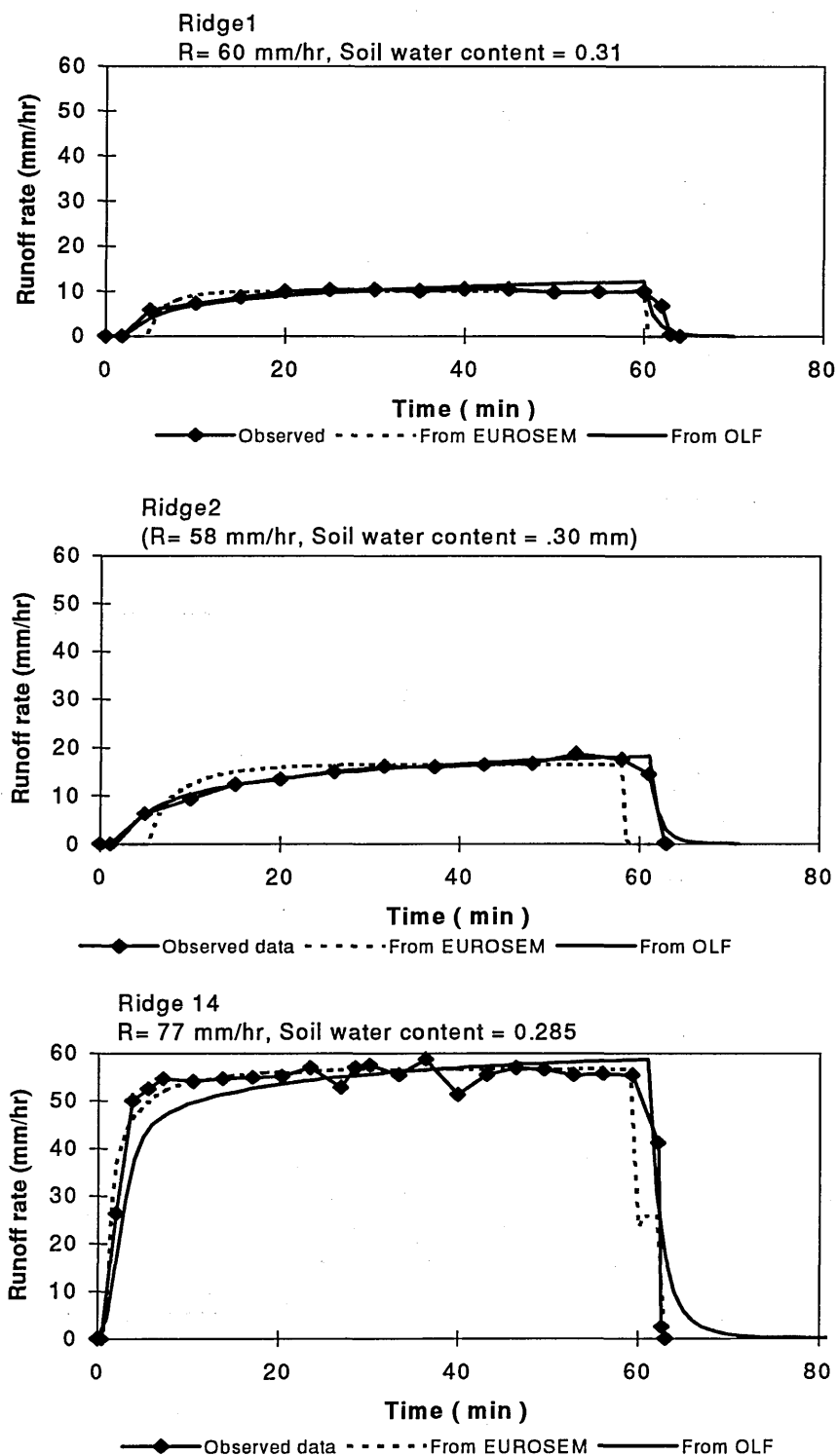


Figure A. 1 Comparison of predicted runoff from EUROSEM and OLF models with observed data (contd.)

Appendix A.1 (contd.)

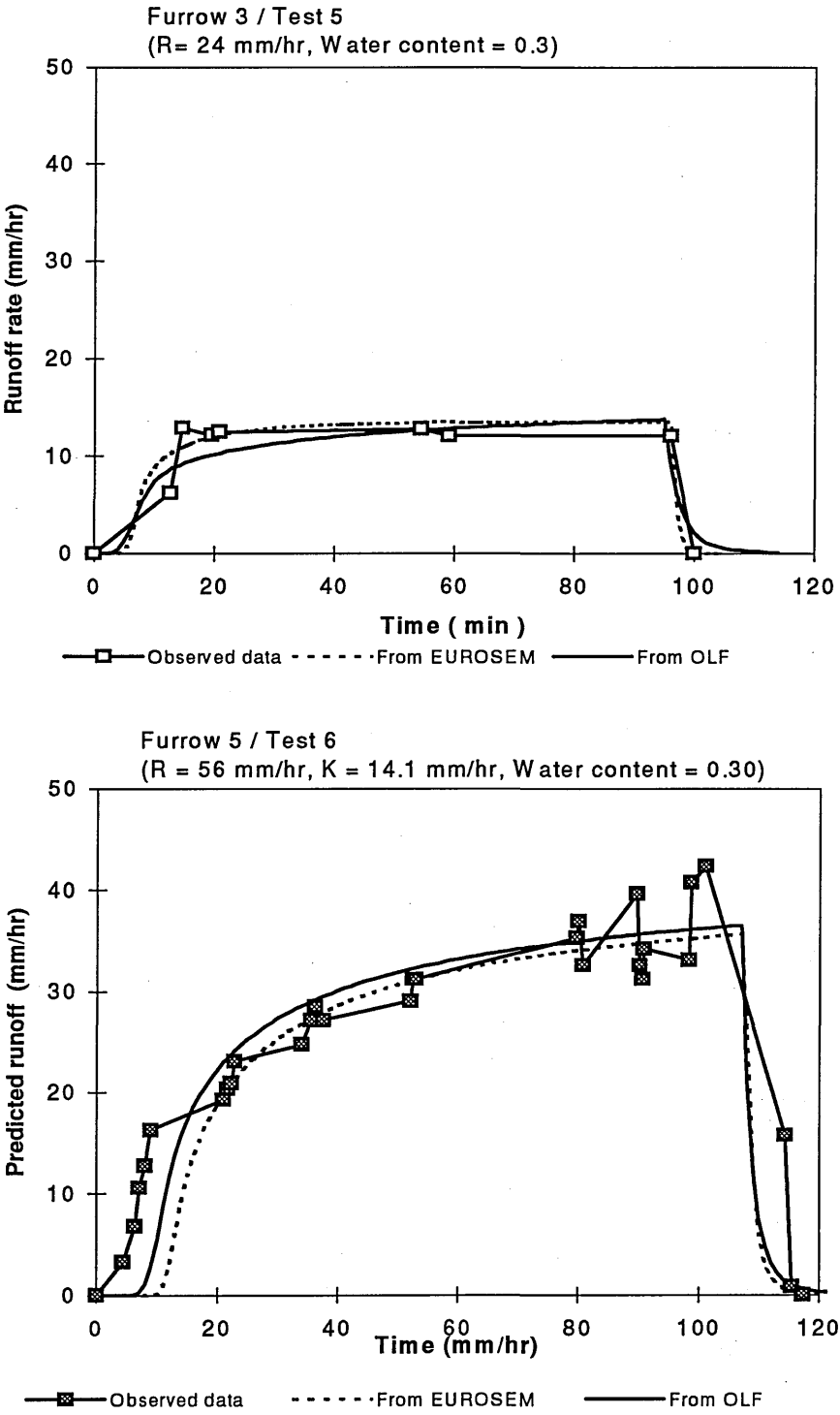


Figure A.1 Comparison of predicted runoff from EUROSEM and OLF models with observed data (contd.)

Appendix A.1 (contd.)**A typical output of OLF model (Furrow 3 Test 5)**

The Length (m) = 12

The Width (m) = 0.2

Application Rate (mm/hr) = 24

Longitudinal Slope = 0.47

Manning's Coefficient (metric) = 0.03

The Time Increment (min) = 1

The Distance Increment (m) = 0.2

Infiltration Coefficient a ($a \cdot t^b$) = 22.947

Infiltration Coefficient b ($a \cdot t^b$) = -0.178

Water Application Time (min) = 93.07

Initial Moisture Content (Volumetric) = 0.3

The Side Length (m) = 0.45

The Side Width (m) = 0.2

The Side Slope = 0.56

The Side Manning's Coefficient (metric) = 0.03

The Side Distance Increment (m) = 0.15

The Side Infiltration Coefficient a ($a \cdot t^b$) = 22.947

The Side Infiltration Coefficient b ($a \cdot t^b$) = -0.178

Initial Moisture Content of Side (Volumetric) = 0.3

Time (min)	Rainfall (mm/h)	Depth (mm),	q (m^2/h)	Q _r (mm/h)
0	24	0	0	0
1	24	0.01	0.003	0.1
2	24	0.036	0.029	0.4
3	24	0.069	0.083	1.3
4	24	0.104	0.166	2.5
5	24	0.137	0.263	4

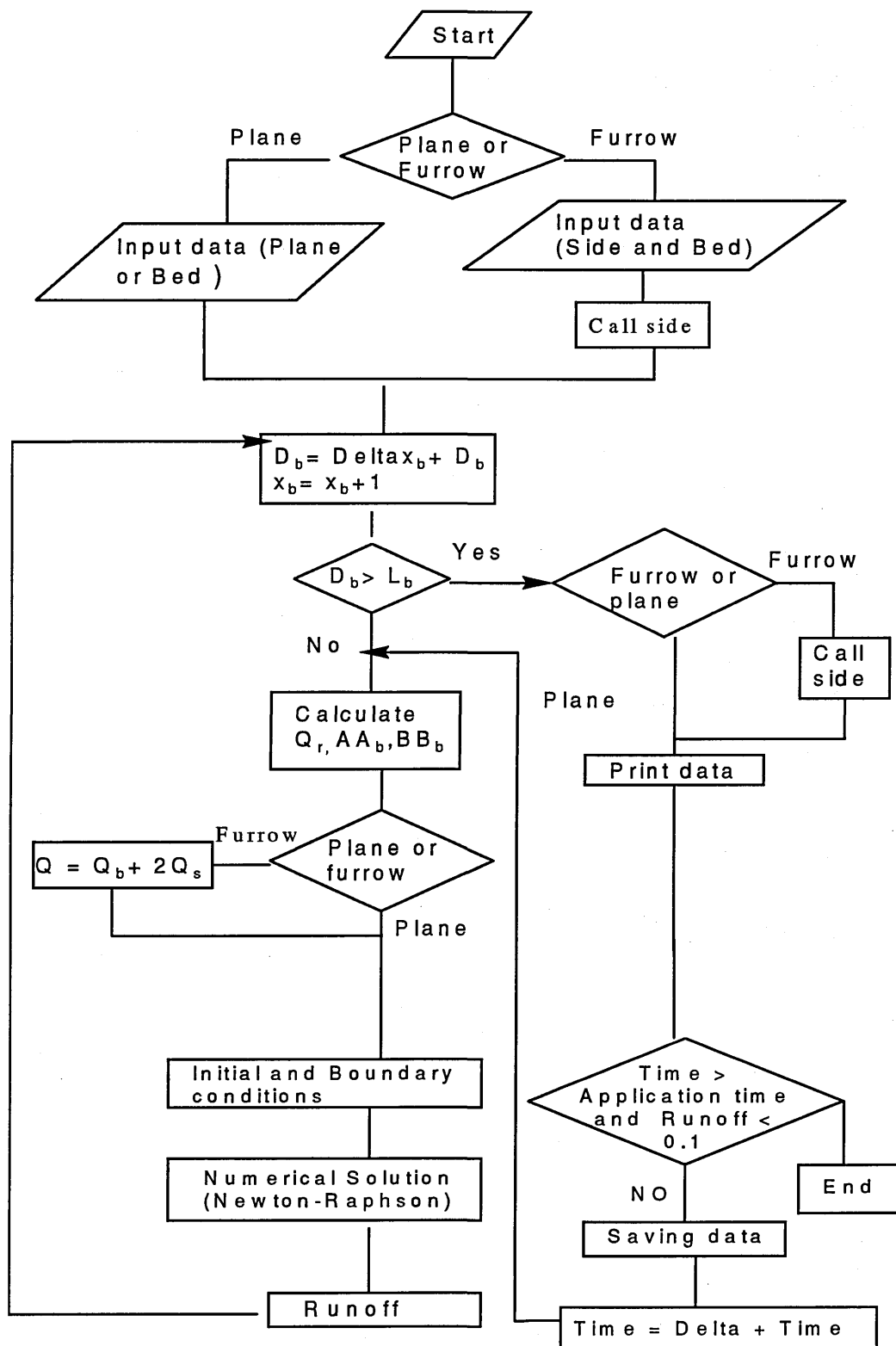
6	24	0.164	0.356	5.4
7	24	0.184	0.431	6.5
8	24	0.198	0.486	7.4
9	24	0.208	0.526	8
10	24	0.214	0.555	8.4
11	24	0.22	0.578	8.8
12	24	0.224	0.596	9
13	24	0.227	0.612	9.3
14	24	0.231	0.626	9.5
15	24	0.233	0.639	9.7
16	24	0.236	0.651	9.9
17	24	0.238	0.662	10
18	24	0.24	0.672	10.2
19	24	0.242	0.681	10.3
20	24	0.244	0.69	10.5
21	24	0.246	0.698	10.6
22	24	0.248	0.706	10.7
23	24	0.249	0.713	10.8
24	24	0.251	0.72	10.9
25	24	0.252	0.726	11
26	24	0.253	0.733	11.1
27	24	0.254	0.738	11.2
28	24	0.256	0.744	11.3
29	24	0.257	0.75	11.4
30	24	0.258	0.755	11.4
31	24	0.259	0.76	11.5
32	24	0.26	0.764	11.6
33	24	0.261	0.769	11.7
34	24	0.262	0.773	11.7
35	24	0.263	0.778	11.8
36	24	0.263	0.782	11.8

37	24	0.264	0.786	11.9
38	24	0.265	0.79	12
39	24	0.266	0.794	12
40	24	0.266	0.797	12.1
41	24	0.267	0.801	12.1
42	24	0.268	0.804	12.2
43	24	0.268	0.807	12.2
44	24	0.269	0.811	12.3
45	24	0.27	0.814	12.3
46	24	0.27	0.817	12.4
47	24	0.271	0.82	12.4
48	24	0.272	0.823	12.5
49	24	0.272	0.826	12.5
50	24	0.273	0.828	12.6
51	24	0.273	0.831	12.6
52	24	0.274	0.834	12.6
53	24	0.274	0.836	12.7
54	24	0.275	0.839	12.7
55	24	0.275	0.841	12.7
56	24	0.276	0.844	12.8
57	24	0.276	0.846	12.8
58	24	0.277	0.848	12.9
59	24	0.277	0.851	12.9
60	24	0.277	0.853	12.9
61	24	0.278	0.855	13
62	24	0.278	0.857	13
63	24	0.279	0.859	13
64	24	0.279	0.861	13.1
65	24	0.279	0.863	13.1
66	24	0.28	0.865	13.1
67	24	0.28	0.867	13.1

68	24	0.281	0.869	13.2
69	24	0.281	0.871	13.2
70	24	0.281	0.873	13.2
71	24	0.282	0.875	13.3
72	24	0.282	0.877	13.3
73	24	0.282	0.878	13.3
74	24	0.283	0.88	13.3
75	24	0.283	0.882	13.4
76	24	0.283	0.883	13.4
77	24	0.284	0.885	13.4
78	24	0.284	0.887	13.4
79	24	0.284	0.888	13.5
80	24	0.285	0.89	13.5
81	24	0.285	0.891	13.5
82	24	0.285	0.893	13.5
83	24	0.285	0.894	13.6
84	24	0.286	0.896	13.6
85	24	0.286	0.897	13.6
86	24	0.286	0.899	13.6
87	24	0.287	0.9	13.6
88	24	0.287	0.902	13.7
89	24	0.287	0.903	13.7
90	24	0.287	0.904	13.7
91	24	0.288	0.906	13.7
92	24	0.288	0.907	13.7
93	24	0.288	0.908	13.8
94	0	0.227	0.61	9.2
95	0	0.179	0.411	6.2
96	0	0.142	0.281	4.3
97	0	0.115	0.195	3
98	0	0.094	0.139	2.1

99	0	0.077	0.101	1.5
100	0	0.065	0.076	1.1
101	0	0.055	0.057	0.9
102	0	0.047	0.044	0.7
103	0	0.041	0.035	0.5
104	0	0.036	0.028	0.4
105	0	0.032	0.023	0.3
106	0	0.028	0.019	0.3
107	0	0.025	0.016	0.2
108	0	0.023	0.013	0.2
109	0	0.021	0.011	0.2
110	0	0.019	0.01	0.1
111	0	0.017	0.008	0.1
112	0	0.016	0.007	0.1
113	0	0.015	0.006	0.1
114	0			0

Appendix A.1 (contd.)



Flow chart of OLF model

Appendix A.2 Input requirements for EUROSEM (Morgan 1994)**Rainfall:**

Rainfall depth (mm) for each time step in the storm (R)

Duration of the storm (min)

Soil physical condition:

Detachability index (g.j) (k)

Settling velocity of the soil particles (m/s) (v_s)

Cohesion (kPa) of the soil at saturation (COH)

Median particle size (μm) (D50)

Manning's n for soil particle roughness (n)

saturated hydraulic conductivity (K_s)

Soil water content (THI)

Catchment geometry and topography:

Width of slope segment (m) (W)

Length of the slope segment (mm) (L)

Roughness ratio (RR)

Slope steepness (m.m) (S)

Manning's n for microtopographic roughness (n_t)

Number of concentrated flow paths per m width (DEPNO)

Average depth of concentrated flow paths (m) (RILLD)

Average width of concentrated flow paths (m) (RILLW)

Side slope of concentrated flow paths (rills) (1:X) (Z)

Vegetation:

Percentage of vegetation cover (COV)

Maximum depth of interception storage (mm) ($IC_{\max}$)

Average acute angle of plant stems to ground ($^\circ$) (PA)

Plant shape factor (grasses/others) (SHAPE)

Percentage basal area of plant stems (PBASE)

Average height of plant canopy (m) (PH)

Manning's n for the plant-induced roughness (n_v)

Appendix B.1 Saturated hydraulic conductivity values for the field experiments

Sample	Measured from falling head		Water balance method	
Column 1	Column 2 Disturbed.*1	Column 3 Undisturbed.	Column 4	Column 5
1	38	10	Furrow 7/Test 3	27
2	50	2.6	Furrow 2/Test 5	12.3
3	29	6.8	Furrow 3/Test 5	13
4	28		Furrow 9/Test 5	6.4
			Furrow 5/Test 5	8.6
			Furrow 7/Test 5	13.4
			Furrow 5/Test 6	4
Mean values =	36	6.5		

Note1: (7),(26),(190) mm/hr are low, mean and high values of saturated hydraulic conductivity reported in the KINEROS user guide (Woolhiser et al, 1990).

Appendix B.2 Comparison between calibrated and calculated capillary drive (G, mm)

Trial	Calibrated	From Smith's equation
Simple plane: (laboratory)		
Plane 14	23.3	52
Plane 18	23.3	13
Plane 19	23.3	19
Mean	23.3	28
Ridge and Furrow: (laboratory)		
Ridge 8	16.6	50
Ridge 9	16.6	4
Ridge 14	16.6	48
Mean	16.6	34
Ridge and furrow: (Field)		
Furrow9/Test 3	11	59
Furrow5/Test 3	11	18
Mean	11	38.5
From time to ponding	0.6, 8, 128 mm	
From literature	98,248, 526	

* Mean of three field time to ponding tests

Appendix C.1 Sensitivity classification of the sensitivity of EUROSEM outputs to changes in input parameters (Quinton 1994)

Parameter- indicates Govers interill equation	Soil loss (t/ha)	Runoff volume (mm)	Peak sediment discharge (kg/min)	Peak discharge (mm/hr)	Time to peak sediment discharge (min)	Time to peak discharge	Time to runof f (min)
THIMX	***	***	***	***			**
XL	***	*	***	*			
THI	***	***	***	***	*	*	*
PLANTB	***	***	***	***	***	***	***
SIR	**	**	**	*	*		
SIR*	**	*	**	*	*		
INRMN	**	*	**	*	*		
SRIL*	**	*	**	*			
RILMN*	**	*	**	*	*		
COH*	**		**		*		
INRILMN	**	*	**	*	*	*	
FMIN	**	**	*	*	*		
RIMN	**	*	**	*	*		
EROD*	**		**				
DEPNO	**	*	**	*	*		
D50	**		**	*			
SRIL	**	*	*	*	*		
G	**	**	*	*	*	*	***
RILLW	*	*	*	*			
COVER	*	*	*	*	*		
EROD	*		*		*		
PLANGLE	*	*	*	*	*		*
PLANTH*	*		*				
ZLR	*		*		*		
RILLD	*		*	*			
DINTR	*	*	*	*	*		
RFR	*	*	*				
COH	*		*		*		
PLINTH	*		*				

A blank indicates insensitivity

* Indicates low sensitivity

** Indicates moderate sensitivity

*** Indicates high sensitivity

Appendix D.1 Characteristics of field tests

Test No	Nozzle size	No of sprinkler	Sprinkler distance	Pressure	Nozzle discharge	Mean Wind speed	Furrow length	Application time	Evaporation rate*	Soil condition
	mm×mm		m	bar	lit/s	m/s	m	min	mm/d	
1	4.8×2.5	9	3		0.68	0.5	12.3	39.83	1	Non-compacted
2	4.8×2.5	9	3	5.25	0.75	7	12.3	121.1	2	Non-compacted
3	5.5×2.5	9	3	3	0.67	7.5	12.3	122.33	0.3	Non-compacted
4	6×3	12	3	3.0	0.81	3	12.3	60.25	2	Compacted
5	6×3	12	3	2	0.59	2.5	12.3	96.07	0.7	Compacted
6	6×3	16	3	3	0.71	3	24.3	107	0.6	Compacted

* Data from climatological station of Silsoe College

Appendix E.1 Catch container data from a moving sprinkler in a stationary position

Distance from irrigator (m)	Volume (Cm ³)	Application rate (mm/hr)	Application rate× Distance from irrigator (mm)(mm/hr)
0	85	16	0
1.5	85	16	24000
3.0	65	12	36000
4.5	125	23	104000
6.0	230	43	256000
7.5	345	64	479000
9.0	385	71	642000
10.5	340	63	661000
12.0	250	46	556000
13.5	120	22	300000
15.0	50	9	139000
16.5	50	1	15000
18.0	0	0.00	0.00
Sum = 117.0			3211000
Average water application rate = (3211000/117000) = 27 mm/hr			