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JAMES COOK UNIVERSITY

Understanding the surface hydrology of low lying sugarcane fields for a basis of optimised surface drainage criteria

A thesis submitted by

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in July 2005

for the degree of Doctor of Philosophy

in the School of Topical Biological

James Cook University

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ABSTRACT

Surface hydrological characteristics of three low lying sugarcane fields in the lower Herbert Valley, North Queensland, were measured and it was found that the regional drainage system controlled the runoff from the field. Low relief slopes and non-integrated drainage design, coupled with high intensity and high volume of rainfall restrict the free movement of water from low lying fields. It was also found that contrary to expectations, inundation of sugarcane fields was not a major cause of yield loss. The recession time for the measured runoff events was between 1.2 and 7.6 hours, well below the critical 72 hours as required for yield loss. The surface water balance of the field shows that the water furrow acts as a preferential pathway for runoff. The surface water balance reveals that, on average only 36% of the runoff from the field exits by the rows. The majority of the runoff (64%) leaves the field via water furrows.

Waterlogging of sugarcane in the heavy textured, far levee soils is caused by the low saturated hydraulic conductivity of the lower soil horizons. This combined with the low specific yield of the soil means that only 100 mm of rain is required to completely saturate the uppermost 1 m of soil. The main study site (Main Palmas Site) was waterlogged for most of the study period (1999-2000).

Evapotranspiration and surface runoff were the significant terms in the annual water balance. Deep drainage contributed more to the annual field water balance than interflow. Sugarcane yields are affected by the presence of shallow watertables. The sugarcane yield components of the 1998-99 crop revealed a strong declining trend across the field bed that was closely related to the depth of the watertable.

It was found that the drainage system behaved such that the flow in the main field flume could be simulated by assuming the water flow from the sugarcane field was being restricted by a high resistance to flow (i.e. Manning's n). This approach was tested over two wet seasons with 16 separate runoff events and it was found that the model SWMM could be used to simulate the dynamics of runoff from the field.

The Youngs watertable model simulated the dynamics of the shallow fluctuating watertable over a period of 2 years of relatively high rainfall. The Rudd and Chardon model predicted the yield of sugarcane well, the predicted yield were the same or very close to the observed yield for three wet seasons, under conditions of excess soil water. Raising the critical watertable depth in the Gayle model from 0.45 m to 0.4 m permitted a reliable predictor of biomass yield of sugarcane.

Optimised surface drainage criteria were established, namely:

- The effect of the trash blanket is to slow the removal of water from the fields however as the drainage water is removed from the field within the 3 day limit, therefore retention of the trash blanket is recommended.
- The upper range of field slopes (0.125%-0.5%) should be such that water is retained on the field to minimise the risk of inundation downstream. To minimise any effects of the high rates of water draining into the regional drainage system, the field slopes should be within the range of 0.01 to 0.125%.
- An optimum field length appears to be between 300 m and 600 m. this range of field lengths is an optimum between minimising the risk of inundation at a field scale and at the same time, reducing the risk of exacerbating the downstream flooding by decreasing the drainage water flow rate to the regional drainage system.

- Water furrows should be retained in fields in areas of high risk of inundation to minimise the effect of inundation.
- Water furrows should be removed from fields in other areas and the additional area planted to sugarcane.

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GLOSSARY

94 net titre
where net titre is a measure of the commercial value of raw sugar for refining purposes. Net titre provides a method for expressing different sugars at a standard value and is used for statistical and payment purposes. The net titre of a sugar is calculated by subtracting the reducing sugar content and five times the ash content from the polarisation of the sugar. It is used in Australia for payment and statistical purposes

$$\text{tonnes 94 net titre} = \frac{\text{tonnes actual x actual net titre}}{94}$$

(Canegrowers 1999)

where
actual net titre = pol – % reducing sugars – (5 x % ash).
% reducing sugars is the percentage of reducing sugars in the sugar, calculated as invert sugar
% ash means the percentage of sulphated ash present in the sugar

advance front
When water is applied to the field, it 'advances' across the surface until the water extends over the entire area.

alternate slope
The slope of the soil surface formed across the width of the field.

anoxic
Lack of oxygen such as the inadequate oxygenation of the soil water. In aquatic environmental chemistry it refers to water that has become oxygen poor due to the bacterial decay of organic matter (Hillel 1998)

aquifer
An aquifer is a porous geological formation that contains and transmits water (Hillel 1998)

Australian Height Datum
Mean sea level for 1966-1968 was assigned the value of zero on the Australian Height Datum at thirty tide gauges around the coast of the Australian continent.

backwatering
When flow in the drainage system becomes impeded, water backs up, which in turn causes the velocity to decrease.

baffle box
A box designed to still the water before it flows into a flume

billet planter
A planting machine that plants cane billets

billets
Lengths of cane, usually between 300-500 mm long

bio-pores
Large soil pores, usually in excess of 2 mm that were created by soil fauna (Hillel 1998)

brix
Total soluble solids per cent in juice
Brix % = sugar % in water and sugar liquid only

cane yield
The biomass yield of sugarcane, the mass of cane harvested from the field

CCS
See commercial cane sugar

colluvial
Material deposited under influence of gravity on steep slopes: mostly sand, silt and angular bedrock fragments. (Hillel 1998)

commercial cane sugar
The sugar content of cane as it is purchased by sugar mills
CCS = pol in cane – 0.5 (brix-pol)

cross slope
The slope over the width of the field (same as alternate slope)

cutthroat flume
Cutthroat flumes are flumes with the throat "cut out." They are formed by directly connecting a 6:1 converging section to a similar diverging section. Thus, they consist of a converging level inlet section with vertical sidewalls and a diverging level outlet section also with vertical sidewalls. They do not have any parallel walls forming a straight throat and belong to a class of throatless flumes. (Skoerboe 1972)

decile rain
Decile is a term for denoting thresholds or boundary values in frequency distributions. The Decile 9 is that value which marks off the 90 per cent of the observations from the rest, the Decile 5 is the same as the median, and the Decile 1 is lower than all but the lowest but 10 per cent of the values.

deep drainage
The amount of water that drains below the rootzone (Hillel 1998)

depth discharge
The relationship between the depth of the water and the volume of discharge (Maidment 1993)

down slope
This term refers to the slope along the length of the field.

drain density
The length of drain per unit area, usually reported in meters of drain per hectare of drained area

drainage board
Statutory bodies formed under the Queensland State Government Financial Administration and Audit Act 1977 and Queensland State Government Statutory Bodies Financial Arrangements Act 1982. Drainage boards function to provide a co-ordinated drainage system for the removal and disposal of excess water from agricultural lands (QNRM 2001)

drainage outfall
The location at which the drain flows into a larger drain or a river

drainage slopes
The surface slope formed by laser grading to allow drainage of fields

duplex soil
A soil where there is a clear or abrupt contrast in the texture between the A and B horizons (Isbell 1996)

Dupuit-Forchheimer
An assumption developed by Dupuit and extended by Forchheimer that states that; In a system of gravity flow towards a shallow drain all flow is horizontal and the velocity at each point is proportional to the slope of the watertable but independent of depth (Hillel 1998)

energy slope
Slope of the water surface under free flow

equivalent depth
The equivalent depth recognizes the fact that the watertable is higher, for a given rainfall rate, with an impermeable layer present than it would be, if the soil was infinitely deep (Youngs 1985)

evapotranspiration
Conversion of liquid water to vapour both by evaporation and by transpiration of the water by plants (Hillel 1998)

excess water
Water that is more than necessary for plant growth, and limits access to the field for farming operations (Gayle *et al.* 1987)

exfiltration
Water flowing out of the soil Moore and Foster (1990)

far levee
The back plain of a catenary sequence across a river floodplain, usually having heavy textured soils such as clays Wilson and Baker (1990)

floodgates
A gate used to control the flow of a body of water

flumes
Flumes are shaped, open-channel flow sections that force flow to accelerate. Acceleration is produced by converging the sidewalls, raising the bottom, or a combination of both (Ackers 1978)

free flow
A flow in a channel which is not affected by the level of the tail water. Free flow is more precisely defined by the Froude number which is the ratio between inertial forces and the gravitational forces (Moore and Foster 1990)

fresh and dry cabbage weight
Cabbage refers to the mass of the leaf above the sugarcane stalk, usually called the cane top. The material is weighed green and referred to as fresh, the cabbage is dried at 60^{o}C for 24 hrs

fresh and dry fibre weight
Cane is squeezed through a series of rollers to extract the juice. The residual material is called the fibre. The material is weighed green and is referred to as fresh. The fibre is dried at 60^{o}C for 24 hrs and is referred to as dry

fresh and dry live leaf weight
Live leaf refers to the green below the cabbage. The material is weighed green and referred to as fresh, the leaves are dried at 60^{o}C for 24 hrs and is referred to as dry.

fresh and dry stalk weight,
The stalk is the main cane stem. The material is weighed green and referred to as fresh, the cane is dried at 60^{o}C for 24 hrs is dry.

green cane trash blanket
Remnants of the previous crop and consists of chopped stalk and leaves of the sugarcane plant discarded during the previous harvest

harvest season average
As the harvest season extends for about 6 months the yield of cane and CCS is averaged over this time to compensate for the effect of time of harvest on yield and CCS.

Herbert River Productivity and Protection Board
The Cane Protection & Productivity Board (CPPB) for the Lower Herbert Valley, Each board consists of representatives from the milling and growing sectors and BSES, and employs staff to assist with disease and pest control as well as assisting growers to improve their productivity. A CPPB provides suitable advice and help to cane growers within its area about the prevention, control and eradication of pest infestation of cane or any other matters that adversely affect the quantity or quality of crops of cane. Each board helps and cooperates with other organizations involved in cane pest and disease research, and production, harvesting, transport and processing of cane. Boards provide advice and information about the preservation and enhancement of the capacity of land to sustain crops of cane (J Reghenzani pers comm.).

hilled up
Soil that is moved from the interrow space to the row to form small hills or rows. The term usually refers to the farming operation that occurs after planting of cane when soil is moved from the interrow space on to the emerging cane.

hodograph
A group of line segments created by connecting the endpoints of each of vectors, the first derivative of a curve (Shene 2000)

Hortonian flow
See rainfall excess flow

hydraulic conductivity
Specifically, hydraulic conductivity is the proportionality factor between the rate of flow through a unit cross sectional area and the potential energy or hydraulic gradient of the flow. More generally the hydraulic conductivity is the ability of the medium to transmit liquid (Hillell 1998)

hydrograph
A graph showing flow rates or water levels with respect to time. A stream hydrograph commonly shows rate of flow; a well hydrograph commonly shows water level (Hillel 1998)

hypoxic
Soil with a low oxygen content (Hillel 1998)

instantaneous discharge
Rate of fluid flow passing a given point at a given moment in time, expressed as volume per unit of time (Maidment 1993)

interflow
The runoff infiltrating into the surface soil and moving toward streams as shallow, perched ground water above the main ground water system (Ritzema 1994)

Interrow
The space between two rows

inundation
The effect of free surface water at some depth above the soil surface on the growth of sugarcane

isohyets
A line drawn on a map connecting points that receive equal amounts of rainfall (BoM 2000)

laser levelling
the practice of forming slopes of fields using laser beacons to control the land forming process

leaf area index
the sum of leaf area of all leaves divided by the area covered by the leaves (Hillel 1998)

levee
The natural ridges that have occurred from deposition of light textured soil from flood events (Wilson and Baker 1990)

long-throated flumes
Long-throated flumes control discharge rate in a throat that is long enough to cause nearly parallel flow lines in the region of flow control. Parallel flow allows these flumes to be accurately rated by analysis using fluid flow concepts (Bos 1978)

mean annual wet season rainfall
The average rainfall recorded for the wet season

modulus of drainage
A constant of proportionality between discharge (Q L/s) and area drained (A m^2) (Connor and Fox 1977)

moisture retention
The relationship between soil moisture potential and soil moisture content (Hillel 1998)

mole drains
Mole drains are unlined cavities in the soil and are installed by plough that draws a torpedo-like mole through the soil at a given depth usually about 0.5 m.

one inch to one chain
The recommended slope formed on a sugarcane field in the Lower Herbert Valley, corresponds to 25.4 mm (one inch) per 20.116 m (one chain) (J Reghenzani pers comm.)

overland flow
Water flowing over the soil surface towards rills, rivulets, channels and rivers (Ritzema 1994)

overtopped
When water enters a field from the surrounding farmland

peak rainfall rate
The highest rate of rainfall recorded for a rainfall event

pedo-hydrological units
Areas of soil that have similar hydrological properties, particular reference to the saturated hydraulic conductivity (Timmer 1998)

perched watertables
Unconfined groundwater separated from an under-lying main body of ground water by an unsaturated zone (Hillel 1998)

phreatic aquifer
A geologic formation of permeable material that has a watertable as the upper surface (Hillel 1998)

pol
the sucrose content of the sugar expressed as degrees of polarization ascertained by polarimetric analysis (Canegrowers 1998)

polder type design
A design that is similar to a polder

polder
tract of lowland reclaimed by the construction of parallel hills (J. Reghezani pers, comm.)

principal profile form
Represents the complete concept and character of the soil profile form (Northcote 1979)

process model
Computer models that simulate the underlying biophysical processes

quickflow
Water that flows out of the catchment on the same day as the rainfall event

radial flow
the flow below the depth of the drain flowing towards the drain (Youngs 1985)

rainfall excess flow
overland flow caused by rainfall in excess of the soil infiltration rate (Moore and Foster 1990)

rating curve
A function that relates the height of open channel flow to the discharge at the point of measurement (Maidment 1993)

ratoon
The new cane which grows from the stubble left behind after harvesting (Canegrowers 1998)

redox
The oxidation-reduction potential (Hillel 1998)

redox probes
Measurement probes that measure the redox potential of the soil.

reduction potential
The potential that is generated between an oxidation or reduction half-reaction and the standard hydrogen electrode

residual or surface storage
Water that accumulates on the soil surface in surface depressions and cannot drain away (Moore and Foster 1990)

resistance to flow
The frictional forces that flow experiences (Maidment 1993)

Reynolds number
The ratio of inertial force to viscous force in a liquid (Moore and Foster 1990)

runoff
That part of precipitation contributing to streamflow (Hillel 1998)

run on
Water that is allowed to run down an inter row space or artificial channel

San Dimas flumes
A special flume that has been designed to obtain flow measurements with high sediment load. The flumes are trapezoidal supercritical-flow flumes requiring extensive head drop to operate (Wilm *et al.* 1932)

saturated hydraulic conductivity
The hydraulic conductivity of the soil when saturated (Hillel 1998)

saturation excess
Precipitation that cannot infiltrate the soil as the soil is already saturated with water (Moore and Foster 1990)

scenario simulations
Model simulations using different model inputs commonly called "what if" scenarios

shallow wells
A shallow bore that is slotted to the just near the surface of the soil. Used to measure watertable fluctuations

short-throated flumes
Short-throated flumes are considered short because they control flow in a region that produces curvilinear flow. Although they may be termed short throated, the overall specified length of the finished structure, including transitions, may be relatively long (Ackers 1978)

single ring infiltrometers
Device to measure soil infiltration rates. A single ring is inserted into the soil and sealed and filled and the depth noted. Changes to the water depth and corresponding time are recorded. From these measurements the infiltration rate can be determined (Hillel 1998)

specific yield
The amount of water released to the groundwater or absorbed by the unsaturated soil with a unit change of height in the watertable (Youngs *et al.* 1989).

stormflow
The runoff infiltrating into the surface soil and moving toward streams as shallow, perched ground water above the main ground water system

stress day index
A method to measure the effect of the crop's sensitivity to environmental factors such as waterlogging during different growth stages to yield (Hiler 1967)

sub-surface drainage
The practice of digging pipes, ditches or mole drains into which groundwater flows into. The main purpose of drainage is usually to increase agricultural productivity (Hillel 1998)

submerged flow
when the downstream flow conditions affect the upstream flow conditions (Moore and Foster 1990)

surface drainage
the diversion or orderly removal of excess water from the surface of the land by means of improved natural or constructed channels, supplemented when necessary by shaping and grading of the land surface to such channels (Ritzema 1990)

tail water
The excess surface drainage water usually left after irrigation.

texture-contrast
Soils with a sharp increase in texture, a sudden increase in clay content, on passing from the surface horizon to subsoil (Isbell 1996)

three day, three year, return rainfall event
A three day rainfall event that has one chance in three years of being exceeded in any future one-year period

time domain reflectometery probes
A method of measuring soil wetness based on the high dielectric constant of water compared to that of soil (Hillel 1998)

total event discharge
The total volume of runoff drained from the field from a rainfall event

trash blanket
See green cane trash blanket

ultrasonic doppler flow velocity meter
Meters based on the principle that transit time of an acoustic signal along a known path is altered by the fluid velocity. A high frequency acoustic signal sent upstream travels slower than a signal sent downstream. By accurately measuring the transit times of signals sent in both directions along a diagonal path, the average path velocity can be calculated. Then, knowing the path angle with respect to the direction of flow, the average axial velocity can be computed (Water Measurement Manual 2000)

unit hydrograph
A hydrograph having a volume of 25 mm of runoff which is associated with a precipitation event of specified duration and areal pattern (Chow *et al.* 1988)

volumetric soil moisture content
The fractional content of water in the soil expressed as a volume of the total soil sample.

water balance
Balance of input and output of water within a given defined hydrological area

water furrows
A ditch 0.4 m deep with gently sloping sides usually placed every 14-18 rows. They are used to transport water away from the rootzone

waterlogging
The occurrence of a watertable at some depth below the soil surface with a subsequent negative effect on the growth of sugarcane. The sugar industry has recognized that if a watertable occurs at a depth of less than 0.5 m in the soil then the field is defined as waterlogged (Rudd and Chardon 1977).

watertable drawdown model
A model that simulates water being withdrawn from an aquifer or watertable. Drawdown is the distance the water table or pressure surface is lowered at a given point

watertable
The top of the water surface in the saturated zone of an unconfined aquifer or the upper surface of the zone of saturation in which the pressure is atmospheric (Hillel 1998)

weirs
An overflow structure built perpendicular to an open channel axis to measure the rate of flow of water. Inspecting and checking the critical parts of weir structures for degradation and improper operation is easy (Ackers 1978)

wet season
The wet season refers to the summer period where high rainfall can occur. In the study area, this season typically considered to begin in early December and finishes in April.

whole stick planters
Sugarcane planting machines that use whole canes or sticks instead of billets

yield potential
The highest possible sugarcane yield obtainable with ideal management, soil, and climate

SYMBOLS USED IN THE TEXT

∇ is the water surface

A area drained (m^2)
A_f is the area of the field (m^2)
A_c is the area of the total catchment (m^2)
A_m is a dimensionless shape factor for the ditch layout and varies from between 0.5 for square to 0.911 for rectangular areas
A_t is the contributing basin area at time t (m^2).
a_p (m^2/hr)
α is an empirical parameter (m^{-1})
α_f is the exponent of depth of flow
α_d is a dimensionless factor dependant on d

B parameter that depend on the soil properties (m/hr)
b is the depth to impermeable layer if the division between the drained layer and the impermeable layer is above the base of the ditch (m)
β is a dimension factor (dimensionless)

C is the discharge coefficient
Cf is the free flow coefficient
Ch is the Chézy Roughness coefficient (m/s)
CN is the curve number with a range of 1-100
CSi is the crop susceptibility factor
$\chi$is the reaction factor (per hr)

D is half the distance of the drain spacing (m)
DD is deep drainage (mm)
DUL is the drained upper limit of the soil in that layer (mm^3/mm^3)
d is the depth to impermeable layer (m)
d_w is the depth of water (m)
d_e is the equivalent depth of the soil (m)
d_p is depression storage
Δ represents the slope of the saturation vapour pressure temperature relationship
ΔH is change in watertable height (m)
Δt is the time increment between the steady states (h)
$\delta H/\delta t$ is the rate of change in watertable height (m/d)

ET is evapotranspiration (mm)
ETo is the potential evapotranspiration (mm/d)
ea actual vapour pressure (kPa)
es - ea saturation vapour pressure deficit
es saturation vapour pressure (kPa)

F is the cumulative infiltration (m)
Fr is the Froude number
f is the friction factor (dimensionless)

f_0 is the infiltration rate of the soil (m/hr)

G is the soil heat flux (MJ/m^2/day)
g is the acceleration due to gravity (m/s^2)
Γ is the wetted cross section (m^2)
γ is the psychrometric constant (kPa/°C)

H is height of watertable at position X (m)
H_0 is the water height in the drain (m)
H_{max} is the maximum watertable height at the mid point between the drains (m)
H_m is the mid height of the watertable from impermeable layer (m)
H_p is the pressure head (m)
h is the depth of water (m)
h_a is the upstream depth (ft)

IF is interflow (mm)
I is the depth water that infiltrated the soil (mm)
i* is the rainfall excess (m)
i=-1 when (Ho/D)αd<V/K1
i=1 when (Ho/D)αd>V/K1

j=0 when Hm<b
j=1 when Hm>b

K is the saturated soil hydraulic conductivity (m/hr)
KH is the horizontal saturated hydraulic conductivity (m/hr)
Kh is a coefficient (L/s)
K0 is hydraulic conductivity of the slowly permeable layer (m/hr)
K1 is hydraulic conductivity of the drained layer (m/hr)
k=0 when Ho<b
k=1 when Ho>b

L is the length of the flume (ft)
Λ is the latent heat of vaporization (MJ/kg)

M is the number of pulses of rainfall
MD modulus of drainage (L/s/ha)
m is the exponent
μ is the number of days in the growth stage (days).

n is the Mannings coefficient of roughness (dimensionless)
n1 free flow exponent

Observed yield is the yield measured at the site

Ps is storm rainfall (m)
Potential yield is the maximum observed yield for the site

Q is the discharge (cu ft/sec)
Q_{md} discharge (L/s)

Q_n is volume of direct runoff
Q_s is storm runoff (m)
q is discharge (m^3/s)
qr is the steady flux which maintains the watertable at a steady state (m)
qsr steady rainfall rate (m/hr)
qt is the discharge (mm/hr)
$q_{\frac{t_p}{e}}$ the discharge at the time of the peak flow rate from runoff initiation divided by the natural log e
θ is the volumetric moisture content (m^3/m^3)
θr is the residual volumetric moisture content (m^3/m^3)
θs is the saturated volumetric moisture content (m^3/m^3)

R is rainfall (mm)
RO is runoff (mm)
RR is the depth of runoff from the row in the field (mm)
Re is excess rainfall (mm/hr)
Rf is the depth of runoff from the field (mm)
Rn is the net radiation ($MJ/m^2/day$)
Ru is depth of runoff (mm)
R0 is the hydraulic radius (m)
r0 is the radius of the drain (m)

S is the specific yield (m/m)
SDi is the stress day factor for the stage of plant growth or time period
SDI is the stress day index
SDIW is the is the stress day factor for the cane growing season
SEW45 is the sum of excess water above 45 cm
SW is the volumetric soil water content (mm^3/mm^3)
SWCON is the soil water conductivity (mm/day)
Sb is the bed slope (m/m)
Se is the energy slope (m/m
Sf is the slope of the field
St is dynamic storage (mm)
Σ is the watershed retention parameter (m)

T is mean daily air temperature at 2 m (°C)
t time (hr)
tp time of the peak flow rate from runoff initiation (hrs)
$\frac{t_p}{e}$ is the time of the peak flow rate from runoff initiation divided by the natural log e
$t_{q_{\frac{t_p}{e}}}$ time at which the discharge is equal to the time of the peak flow rate from runoff initiation divided by the natural log e
τ is the recession coefficient (hrs)

U_2 is the wind speed at 2 m height (m/s)
u is the mean flow velocity (m/s)

V is the velocity of the water (m/s)
V_H is the watertable height (m)
Vw is the flux to or from the watertable (positive up) over the time period (1hr) (mm)
V1 is the volume of water (A x d) (m^3)
ς is a flow coefficient (L/s)
ν is the number of stages of crop growth (for sugarcane this is three)

W is the width of the throat (ft)
WFR is the depth of runoff from the water furrow in the field (mm)
Wf is the width of the field

X is the position away from the drain (m)
Xj is the average distance from the soil surface to the watertable during each day (cm)
x is distance between the two points of interest (m)

YR is the relative yield
Yi is the crop yield during growth stage i
Yo is the potential yield
y is the depth of flow (m)
Ψ is the soil moisture potential (m)

CHAPTER 1 INTRODUCTION

1.1 THESIS OBJECTIVES

The aim of this thesis is to develop field design criteria for **surface drainage**[1] of low lying sugarcane fields. The criteria were developed by measurement and modelling of the field scale hydrological processes that influence surface drainage of sugarcane fields subject to **inundation** and **waterlogging** in the Lower Herbert Valley, North Queensland (Fig. 1.1).

1.1.1 Background

Surface drainage of sugarcane fields offers a viable management option to increase the productivity of sugarcane in the Lower Herbert Valley. However, there is little understanding of the hydrological processes that cause both inundation and waterlogging, and of the effectiveness of the current drainage practices to control both. At present there are few systematically tested field drainage design criteria to optimise the productivity of sugarcane in this environment.

In the present study, carried out between January 1998 and December 2000, inundation is defined as the development of free surface water at some height above the soil surface on the growth of sugarcane. Inundation may occur when there is standing water or when the water is flowing. Waterlogging is defined in this study as the occurrence of a **watertable** at some depth below the soil surface with a subsequent negative effect on the growth of sugarcane. The sugar industry has recognized that if a watertable occurs at a depth of less than 0.5 m in the soil then the field is defined as waterlogged (Rudd and Chardon 1977).

[1] Technical terms are defined in a glossary in the front of the thesis. The first time such terms are used they appear in bold.

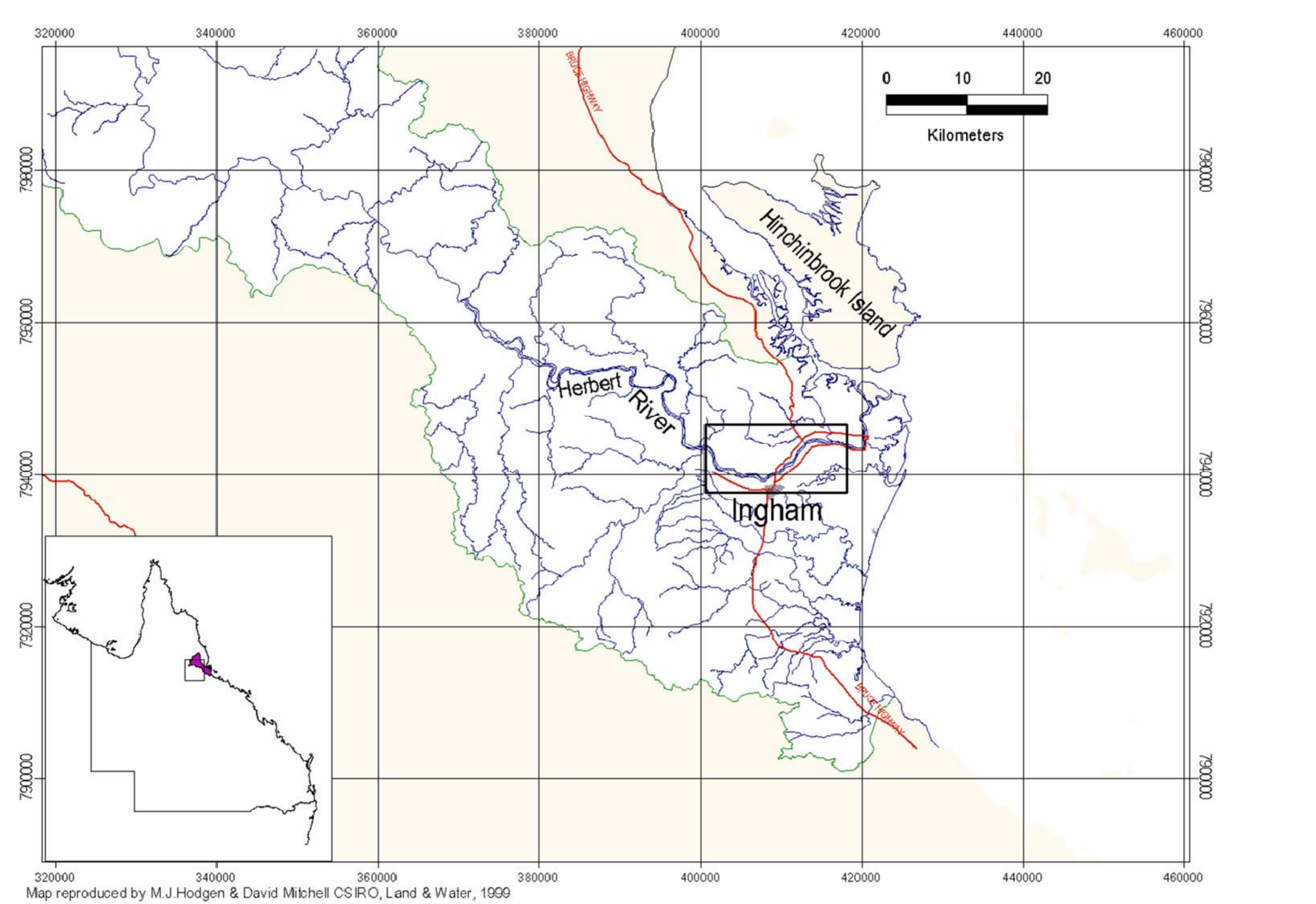

Figure 1.1 Location of the Lower Herbert Valley and of the detailed study area in the rectangle near Ingham coordinate Fig 1.2. (map units in UTM, datum WGS84)

Inundation and waterlogging of low lying sugar cane fields has long been recognized as a major constraint to the productivity of the sugarcane industry in North Queensland (Gutteridge, Haskins and Davey 1976; Cameron MacNamarra 1984; Tait 1995). In the Lower Herbert Valley (Fig. 1.1), the climate, topography, and soils predispose low lying sugarcane fields to inundation by surface water and waterlogging by shallow watertables regularly during the **wet season** (Johnson and Murray 1997).

The Lower Herbert Valley is a major sugar producing area, with up to 60 000 ha of sugarcane grown (Johnson and Murray 1997) that was worth $AUD70 million at the farm gate in 1998 (Australian Bureau of Statistics 2001).

Mean annual rainfall for Ingham, the main urban centre of the Lower Herbert Valley, and of the Hinchinbrook Shire, is 2069 mm (Bureau of Meteorology 2000), and exhibits the summer dominated pattern associated with a monsoon climate (Johnson and Murray 1997). **Mean annual wet season rainfall** for Ingham is 1467 mm with a standard deviation of 519 mm (Bureau of Meteorology 2000).

The Lower Herbert Valley, an area of 3000 km^2, is a coastal floodplain flanked by mountains in excess of 1000 m; the floodplain is characterised by low angle slopes ranging between 0 and 2% (Johnson and Murray 1997). The total area of sugarcane on the flood plain is in excess of 60000 ha (Johnson and Murray 1997). The soils of the floodplain fall into three broad classes, sandy well drained **levee** soils, heavy poorly drained **far levee** soils, and imperfectly drained colluvial soils (Wilson and Baker 1990). The present study focused primarily on the far levee soils.

The duration of inundation of sugarcane in low lying sugarcane fields in the Lower Herbert Valley is relatively short, usually 1-3 days (Section 3.4.4). Inundation is typically the result of a large rainfall event, greater that 75 mm over 12 hours (Section 3.4.4), while waterlogging of low lying sugarcane fields is protracted and can last for many months (Rudd and Chardon 1977; Bohl *et al.* 2000)

Soil layers of low permeability will restrict the infiltration of rainfall and downward movement of the soil water, which may result in the development of shallow **perched watertables**. Waterlogging by the shallow perched watertable may extend for months at a time, and is a major cause of yield loss (Rudd and Chardon 1977; Gayle *et al.* 1987).

1.1.2 Research objectives

The main objectives of the thesis are:

to understand the underlying soil and field hydrological processes involved in the generation of **runoff**, **interflow**, and waterlogging of the soil;

to use the measured field data from the study sites to calibrate suitable computer models to simulate the hydrological processes; and

to use the models to derive optimized field drainage design criteria through modelling of a range of climatic conditions and field designs.

1.2 FIELD SCALE HYDROLOGY AND SUGARCANE RESPONSES TO EXCESS WATER

Sugarcane requires for maximum production and under optimal conditions, approximately 1800 mm of rainfall or irrigation per year and is well adapted to high rainfall areas (Rehm and Espig 1991). However as early as 1855 it was noted that both high watertables in soils (waterlogging) and free surface water (inundation) restricted the **yield potential** of sugarcane

(Agricultural Year Book 1855 cited in Saveson 1950). Efficient surface drainage has long been seen as necessary for the effective production of sugarcane (Stubbs 1895). Removal of **excess water** from fields by drainage has a positive influence on sugarcane productivity and a direct effect on the timeliness of farming operations (van Shilfergaarde 1974).

1.2.1 Key definitions

Excess water is defined in this thesis as water that is more than necessary for plant growth, and limits access to the field for farming operations. This broad definition includes the shallow watertables that may develop in sugarcane fields. Such lands are characterized by low lying floodplains and are particularly prone to productivity losses as a consequence of excess water. The excess water is internally generated from runoff that cannot discharge from the field due to topography or field design, or is restricted from deep drainage by a soil layer of low **hydraulic conductivity**. Alternatively excess water maybe externally generated from the field by drainage systems which fill and overflows onto the surrounding fields or back up on the non draining field.

Surface drainage is defined as the diversion or orderly removal of excess water from the surface of the land by means of improved natural or constructed channels, supplemented when necessary by shaping and grading of the land surface to such channels (International Committee on Irrigation and Drainage 1982). Drainage of the shallow watertable by open channels is also included in this definition of surface drainage.

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1.2.2 Climate conditions that cause excess water

Large volumes and high intensities of rain in the wet season in North Queensland cause water to pond on the soil surface, which in turn creates an environment that is detrimental to sugarcane survival and growth (Kingdon 1991). This is particularly true of the Lower Herbert Valley where mean annual rainfall exceeds 2000 mm and of which 70% falls between December and March

(Section 2.1.2). The highest annual total since 1892 at Ingham was 4552 mm while the lowest was 816 mm (Bureau of Meteorology 2000). High spatial variability of rainfall also occurs with strong rainfall gradients over short distances, this is indicated by the closely spaced mean annual rainfall **isohyets** (Fig. 1.2).

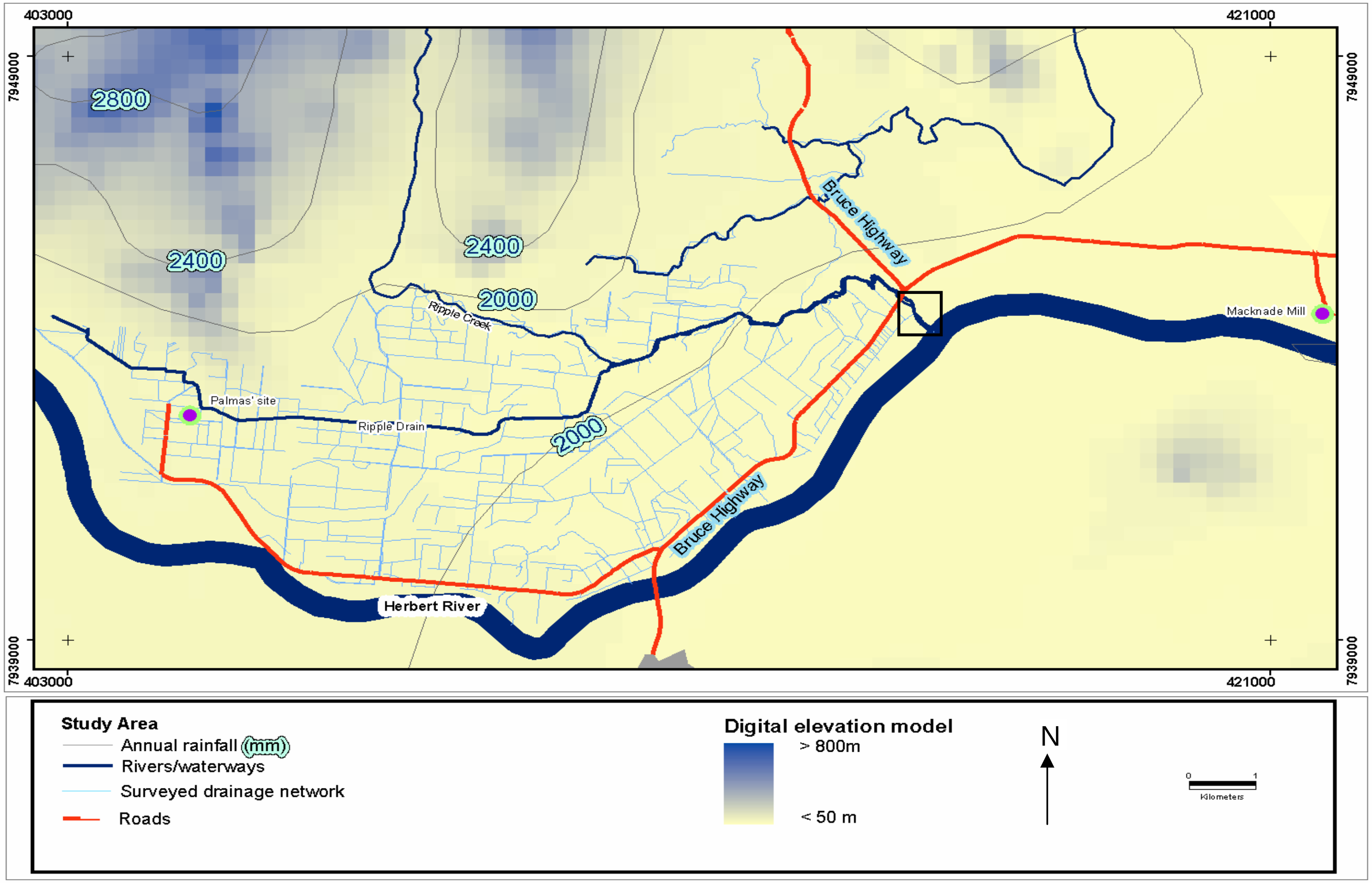


Figure 1.2 Map showing main study site (Palmas) and secondary study site (Macknade Mill), mean annual rainfall isohyets (grey) and roads (red) (coordinates in UTM, Datum WGS 84) Location of this map is shown in Fig. 1.1. (Box shows location of floodgates)

1.2.3 On-farm drainage practices

Cane growers in the Lower Herbert Valley have traditionally incorporated shallow, open, in-field drains, called **water furrows**, into the field design (Fig. 1.3). The water furrows were used in the old manual harvesting system when temporary tram lines were laid down the furrows and flat top wagons were able to travel down the rails to be loaded with cut cane. The water furrows were also included on the assumption that they speed the removal of surface water and that they drain water from shallow fluctuating watertable present in the field.

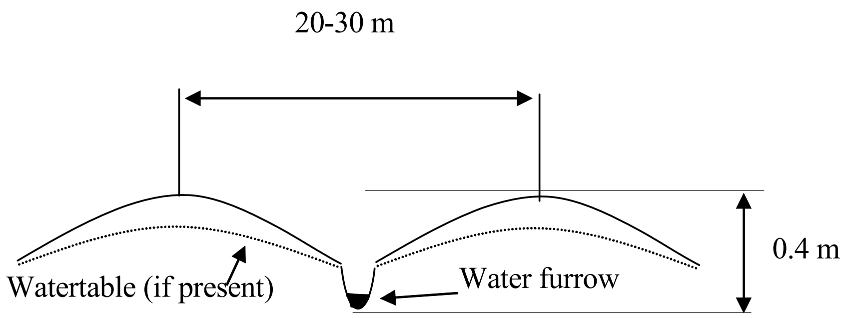


Figure 1.3 Cross section of a typical field layout with water furrows

Since 1982, **laser leveling** has been used by growers, contractors, and technical boards in the Lower Herbert River to form drainage slopes on sugarcane fields. The drainage slopes are believed to increase the effectiveness of surface drainage by reducing surface storage and detention and to increase the speed with which surface water is shed from the field. Recommendations for the parameters of field design such as slope and length have been formulated by the Herbert River Productivity and Protection Board (HRPPB) and the technical field unit of CSR Ltd to minimize the amount of soil moved during the laser levelling operation. These recommendations are summarized in Table 1.1 below.

Table 1.1 Field drainage parameters for sugarcane fields in the Lower Herbert Valley. (Source: Park 1999; Section 2.3.1)

Field feature		Recommended Design
Slope		1:792 equivalent to 1 inch/chain
	Width	2.5 m
Field drain	Depth	0.3 m
	Batter	No recommendation
Water furrows		No recommendation
Drill distances		1.52 m
Field length		300 m
Drain density		No recommendation
Field size		No recommendation

1.2.4 Regional drainage practices

On-farm drainage measures require the establishment of external drainage systems to facilitate the discharge of runoff from the fields of the Lower Herbert Valley. Initially the external drains followed natural drainage lines that were widened, straightened, and subsequently extended to undrained areas. The development of the external drainage system was not planned from a regional perspective but evolved over time in an *ad hoc* manner. During the mid 1960's **drainage boards** were established to optimize and maintain the external drainage network (Horsley *et al.* 1982a).

1.2.5 Previous regional drainage studies

In last 30 years four studies have focused on the improvement of the regional drainage networks within the wet tropics of North Queensland and in particular in the Lower Herbert Valley (Gutteridge Haskins and Davey 1976; Cameron McNamara 1984; Ian Drummond and Associates 1993; Tait 1995). Only the study of Cameron McNamara (1984) developed an empirical relationship between field drainage and the regional drainage system. This relationship was derived from modelling a range of wet season rainfall events on an idealised 20 ha sugarcane (Cameron McNamara 1984). The derivation of the **modulus of drainage** is discussed below.

Gutteridge Haskins and Davey (1976) reviewed the effect of inadequate drainage on the sugar industry and developed simple drainage criteria, from local knowledge. This study recommended that the regional drainage system in the Ingham area remove 50% of the water from sugarcane fields after a **three day, three year, return rainfall event** (Gutteridge Haskins and Davey 1976). From the original report it is difficult to understand how this recommendation was developed. The criterion appears to have no analytical derivation; it may have been developed to prevent damage to sugarcane from common wet season rainfall events.

Cameron McNamara (1984) was commissioned to develop specific recommendations to improve the regional drainage of the Hichinbrook Shire which includes the study area. This included specific earthworks such as channel widening, increased culvert size and more drainage channels. These recommendations were based on a modulus of drainage of 5 L/s/ha for the Hichinbrook Shire that was developed by the modelling of a range of wet season rainfalls on a generalized field of 20 ha (Cameron McNamara 1984).

A modulus of drainage (M_D) (L/s/ha) is a constant of proportionality between discharge (Q_{md} L/s) and area drained (A ha^{-1}) according to equation 1.1 (Connor and Fox 1983):

$$Q_{md} = M_D A \qquad \text{Equation 1.1}$$

Equation 1.1 allows the peak flow rates of runoff from an area of land to be estimated. The peak field flow rates are then used to design regional or farm drains large enough to remove 85% of the runoff from the field within three days from a three day, three year, return rainfall event. This relationship does not however, provide for any design criteria such as length, slope or width for sugarcane fields or how the drainage should be coordinated through the drainage system to prevent inundation further down the catchment. The modulus of drainage is applied to determine the flow rate from a sugarcane field in the context of defining the dimensions of a regional or farm drain to remove that water. It cannot be used to determine the amount of water that will be in the drainage network at a particular point, as it does not take into account the water entering the drain from higher in the drainage network.

In more recent studies Ian Drummond and Associates (1993) and Tait (1995) reviewed the Hinchinbrook Rural Drainage Plan (Cameron McNamara 1984) and proposed that the recommendations of the Hinchinbrook Rural Drainage Plan (Cameron McNamara 1984) be implemented.

1.2.6 Causes of inundation and waterlogging

Two mechanisms cause inundation of sugarcane fields in the Lower Herbert Valley. In the first case rain falling within the catchment fills the regional drainage system beyond the capacity to discharge into the river. This is exacerbated in the detailed study area when the floodgates at the mouth of the Ripple Creek (Fig. 1.2) are closed during high flows in the Herbert River and water from the creek spills out and inundates the lower end of the Ripple Creek Catchment. In the second case, a combination of bank full or greater flow from the Herbert River and high intensity rainfall in excess of the discharge capacity of the Ripple Creek drainage systems leads to widespread inundation across the Ripple Creek Catchment. The uncoordinated development of the regional drainage system means the fields in the lower part of the drainage system are subjected to high volumes of drainage water that can inundate fields, periodically for days at a time (Section 3.4.4).

The occurrence of shallow watertables within sugarcane fields in the Lower Herbert Valley is widespread (Rudd and Chardon 1977; Tait 1995). Approximately 15 000 ha of the Lower Herbert Valley are affected by waterlogging (Tait 1995). Timmer (1998) calculated that about a third of the soil in the agricultural land of the Ripple Creek catchment could be classified as having low permeability. In turn it may be assumed that this area could be prone to waterlogging.

1.2.7 Plant responses to inundation

The effect of inundation on sugarcane growth is not well understood. It is known that the growth of sugarcane subjected to inundation is reduced compared to that of sugarcane not inundated (Sartoris and Belcher 1949; Carter 1980; Deren and Raid 1997). This reduction in growth has been attributed to a number of causes: denitrification, diseases, plant hormonal responses, toxic responses to **hypoxic** or **anoxic** soil conditions, or toxic response to secondary breakdown products of the soil organic matter (Stevens 1948; Carter 1980; Ridge and Reghenzani 2001).

Sugarcane is tolerant of extended periods of inundation (Stevens 1948; Deren *et al.* 1991; Deren and Snyder 1991; Srinivasan and Batcha 1992; Deren and Raid 1997; Bell *et al.* 2000). However, all of these studies also reported that the yield or the yield potential of sugarcane was lowered by inundation. There is no agreement on the critical duration of inundation, which ranges from 10 days (Deren and Raid 1997) to 6 months (Stevens 1948; Srinivasan and Batcha 1992). If the growing point of the sugarcane plant is covered by water, death may occur within 3 days (Gutteridge Haskins and Davey 1976), and if sugarcane is inundated anytime through the growing season the yield potential will be lowered. The degree of damage will depend on the depth and duration of water and the stage of growth (Gutteridge Haskins and Davey 1976).

Research on the effects of inundation and waterlogging on the yield potential sugarcane have been opportunistic usually after an extreme rainfall event, one example is a report of an experiment on yield depression caused by a cyclone in 1947 at the Sugar Plant Field Station at Canal Point Florida (Sartoris and Belcher 1949). The cyclone caused fresh water from Lake Okeechobee, to cover all the fields of about 2000 varieties of breeding cane, initially about 300 - 600 mm above the soil surface (Sartoris and Belcher 1949). However, more rain brought the water level up to 1.5 to 2.0 m with a total period of submergence of 95-105 days (Sartoris and Belcher 1949). The sugarcane died in 2 to 3 days if it had been completely submerged regardless of the variety. Plants that had at least some stalk out of the water developed adventitious roots and survived the 105 days of submergence (Sartoris and Belcher 1949)

In a more structured experiment in Louisiana, a single variety of sugarcane was planted in field plots and subjected to a wide range of excess water conditions (Carter 1980). These treatments ranged from a 4-week flood, a constant 30 cm watertable, and continuously drained at 1.5 m treatment, the inundation treatment also waterlogged the sugarcane (Carter 1980). The yield of sugarcane was higher under flooded conditions (4 week flood) compared to the plots that were drained at 1.5 m which in turn yielded higher than plots with a constant 30 cm watertable for 5 months (Carter 1980). This is consistent with the previous studies that suggest that inundation is detrimental to sugarcane yield, but it also suggests that continuous waterlogging (5 months) is more detrimental to yield than 4 weeks of inundation and waterlogging.

The time of inundation is also important in assessment of the effect of flooding on sugarcane. Deren and Raid (1997) concluded that 10 days of inundation 18 days after planting caused the greatest yield loss of both biomass and sugar compared to other treatments that were flooded after planting. The measured yield components of the sugarcane suggested that the reduced yield of the flooded cane was entirely due to decreased stalk numbers; mean stalk weight and sucrose concentration were not affected (Deren and Raid 1997). The results suggest that as a consequence of the physiology of sugarcane, a clumping grass, any damage to the stool and primary shoots will carry on through the life of the plant (Deren and Raid 1997). Srinivasan and Batcha (1992) found that after 6 months of inundation the tillering habit (stalk number) was suppressed compared to that of uninundated sugarcane.

Other studies have screened for flood tolerance of sugarcane. The conclusion is that some clones of sugarcane can tolerate flooding while other clones cannot (Roach and Mullins 1985; Deren *et al.* 1991).

If the plant is completely inundated, then death will occur within two to three days (Sartoris and Belcher 1949). Partial inundation will reduce the plant's growth and may have subsequent impact on the final yield. The effect of inundation on yield is expressed in the decreased stalk numbers (Srinivasan and Batcha 1992; Deren and Raid 1997) and is not as great as the effect of waterlogging on yield (Carter 1980).

1.2.8 Plant responses to waterlogging

The physiological response of sugarcane to excess water is currently the focus of another study supported by the CRC for Sustainable Sugar Production (Burry pers. comm.). Currently there is little understanding of how excess water effects the growth of sugarcane. There have been a number of studies that have quantified the yield response of sugarcane to the depth of a shallow watertable (Rudd and Chardon 1977; Gayle *et al.* 1987; Deren and Raid 1997).

Two relationships between waterlogging duration and intensity, as measured by depth of watertable, and sugarcane yield response have been developed for clay soils (Rudd and Chardon 1977; Gayle *et al.* 1987). Prolonged waterlogging may cause the soil to become anaerobic which in turn may cause some of the symptoms associated with waterlogging such as reduced plant vigor, stunting of the plant, or yellowing of the leaves (Deren and Raid 1997).

Rudd and Chardon (1977) found that the overall yield of cane was much better on adequately drained sites than on poorly drained soils. This study then quantified the yield loss for waterlogging as every day the watertable is above 0.5 m between December and June the yield will decrease by 0.46 t/ha (Rudd and Chardon 1977).

Gayle *et al.* (1987) found that the critical watertable depth for yield reduction was 0.45 m; shallower watertables decreased the yield of sugarcane. This study compared published yield data obtained from subsurface drained sugarcane to that from undrained sugarcane fields. Studies of the yield components of waterlogged sugarcane have found that the yield was significantly different between plant and second **ratoon** crops (Gosnell 1971). Carter *et al*. (1985) found that sugarcane yield was significantly lower in undrained plots compared to drained plots over a plant and first ratoon cycle. Gosnell (1971) found that sugarcane yield did not decrease if the watertable was kept below 1.0 m. Shallower watertables at 0.75 m, 0.5 m and 0.25 m resulted in significantly lower yields.

The depth of the watertable had a significant effect on the number of stalks grown through the season which declined significantly in the 0.25 m and 0.5 m watertable treatments compared to the deeper watertable treatments (Gosnell 1971). Stalk densities were significantly lower in some planting patterns compared to undrained plots of the same planting pattern for a single harvest (Carter *et al.* 1985). Sugar yields as measured by sucrose concentration were not significantly affected by waterlogging (Gosnell 1971; Carter *et al.* 1985).

Carter (1980) correlated the reduction/oxidation (**redox**) status of a silty clay soil with the yield of sugarcane and found that sugarcane biomass yields declined 28 kg/ha for every day the redox status of the soil (Eh) was less than 332 mV. The time required for the soil to move from an oxidized to reduced form under waterlogged conditions was 4 days (Carter 1980).

The type of soil that inundation and waterlogging studies were carried out on was important to the measured plant response. For example, the study completed by Pitts *et al.* (1993) in the Everglades, Florida, showed an increased yield for crops grown on sandy soil with a watertable at 0.4 m compared to crops grown on a similar soil with a watertable at 0.8 m. While research on sugarcane grown on clay soils concluded that high watertables had a detrimental effect on yield (Rudd and Chardon 1977; Gayle *et al.* 1987), with young cane the most susceptible (Ridge 1972). The effect of waterlogging on sugarcane is dependent on soil type is thought to be related to the restricted internal drainage of heavier textured soil as well as the lower air filled porosity of the soil which may cause a build up of toxic products or induce a hormonal response in the plant (Gayle *et al.* 1987).

Waterlogging of sugarcane grown on clay soils reduces the yield of sugarcane (Gosnell 1971; Rudd and Chardon 1977; Gayle *et al.* 1987). Young sugarcane is more susceptible to waterlogging than more mature sugarcane and this yield reduction is evident in a reduction in the number of stalks present on the plant. The critical depth of the watertable to induce waterlogging stress appears to be about 0.5 m. Although there have been measured decrease in yields at watertables below this, they were not significant (Gosnell 1971).

1.2.9 Hydrological processes in sugarcane fields

The hydrological processes within sugarcane fields are the generation of runoff (including the process of **overland flow**), the **resistance to flow**, and the shallow subsurface flow from the watertable to the water furrows (interflow). The latter has been thought to be the main mechanisms of drainage of the perched watertables within sugarcane fields and is discussed below (Section 4.2).

The processes that control and generate runoff from low lying sugarcane fields that are covered with a thick **trash blanket** are not well understood. Raine *et al.* (1997) reported that increased sugarcane trash levels may increase the resistance to surface irrigation flow; however the effect of a trash blanket was not specifically studied. Low slopes and thick trash blankets characterize sugarcane fields in the Lower Herbert Valley. The trash blanket is a remnant of the previous crop and consists of chopped stalk and leaves of the sugarcane plant discarded during the harvest and is regarded as vital for weed and erosion control. The effects of the trash blanket on the hydrological processes have received little attention to date and were a focus of the present study (Section 3.4.1).

Fluctuating shallow watertables commonly occur in the low lying sugarcane fields of the Lower Herbert Valley (Rudd and Chardon 1977; Bohl *et al*. 1999; Mitchell *et al*. 2000). In general, the processes that control and generate the fluctuating shallow watertables are well known (Hillel 1999). However there is little understanding of the effect of field design on the fluctuating shallow watertables in low lying sugarcane fields. Hence measurement and modelling of the fluctuating shallow watertables were another focus of the present study (Chapter 4).

While there is direct evidence that inundation and waterlogging affect sugarcane productivity (Sections 1.2.7 and 1.2.8), little information is available to indicate which hydrological process leads to inundation and waterlogging on the poorly drained, slowly permeable, alluvial flood plain soils of the Lower Herbert Valley. Consequently, no optimum basis exists for improving the design of field drainage and how the improved field design may affect the response of the drainage network. These effects may be expressed as a changed runoff regime with lower peak flows due to removal of preferential runoff pathways such as water furrows, but more volume discharged from improved drainage of the shallow watertable with a reduced period of waterlogging. The nature of such change is investigated in this thesis (Chapter 5).

1.3 KNOWLEDGE GAPS

The following specific questions are addressed in the present study:

- What field design criteria can be formulated that will decrease the likelihood of low lying fields being inundated?
- Does laser levelling of low lying fields reduce the risk of inundation?
- How do water furrows affect runoff?
- What field design parameters in low lying fields are the most important in managing the runoff process?

- How does a trash blanket affect the generation of runoff from a low lying sugarcane field?
- What are the pathways of runoff from a low lying field?
- What field design criteria can be formulated which will decrease the likelihood of low lying fields being waterlogged?
- What influence does the presence of water furrows have on the perched watertable within a low lying sugarcane field?
- What are the pathways for movement of groundwater in a low lying sugarcane field?
- Can incorporation of improved drainage into field design increase the accessibility and timeliness of farming operations in a low lying field?

To answer these questions a series of field, laboratory and modelling exercises was undertaken that measured and modelled the processes of the surface hydrology of a low lying sugarcane field in the humid tropics.

1.4 STUDY SITES

The location of the main field research, the Palmas Site, was approximately 20 km north west of Ingham, Queensland Australia (Fig. 1.2). The area is within the humid wet tropics of Australia, which receives more than 1500 mm of annual rainfall (Isbell and Edwards 1988). The main study site was selected because it was representative of the poorly drained, low lying sugarcane fields in the area. The poorly drained soil at the main study site was classified as a Kurosolic Redoxic Hydrosol (Isbell 1996; S. Eldridge pers. comm.). The Palmas Site is on a commercial sugarcane farm within the Ripple Creek catchment; a well-defined sub catchment of the Lower Herbert River (Fig. 1.2). The field at the main Palmas Site was laser levelled with water furrows installed in 1995. Located approximately 500 m away on the same soil type was another laser levelled field with no water furrows (Lasered Palmas Site) (Fig. 1.2). The study sites are more fully described in section 2.1.

A third study site was located 10 km east of the Palmas Site near the Macknade Mill of CSR Ltd (Fig. 1.2), where the effects on sugarcane yield of mounding of the rows and different field slopes has been studied by John Reghenzani from the Bureau of Sugarcane Experimental Stations (BSES) Ingham. The surface soil texture is silty clay loam grading into a fine sandy loam and the well drained soil was classified as a Leptic Tenosol/ Stratic Rudosol (Isbell 1996; S. Eldridge, pers. comm.).

1.5 METHODOLOGICAL FRAMEWORK

1.5.1 Soil samples and analysis

The study commenced in December 1997, when a soil pit was dug at the Palmas site to a depth of 0.75 m and soil samples were removed for **moisture retention** and hydraulic conductivity determinations (Section 4.3). In April 1999 another soil pit was dug at the site to a depth of 2.0 m and the soil described (Section 2.1.3), and small undisturbed cores 73 mm in diameter and 50 mm in height were removed for additional moisture retention and hydraulic conductivity determinations. **Single ring infiltrometers** were used to measure the infiltration rate of key soil horizons which in turn was used to estimate the **saturated hydraulic conductivity** of the 4 soil horizons observed in the pit (Section 4.3).

From September until December 1998, a series of experiments was conducted at the Palmas site to establish a **depth discharge** relationship, the resistance to flow of runoff (Section 3.3), and to measure *in situ* soil hydraulic properties (Section 4.3).

Field measurements of a range of hydrological processes took place during the wet seasons of 1998-99 and 1999-2000. **Flumes** were installed to measure the runoff from the fields (Section 3.3) and **shallow wells** were installed to observe and measure the fluctuating shallow watertable (Section 4.3). **Time domain reflectometery probes** (TDR) were installed to measured the **volumetric soil moisture content** at several depths (section 4.3) and **redox probes** were installed to measure the **reduction potential** of the soil at two depths in the field (Section 4.3).

Soil samples from the study site were used in the laboratory to determine soil water retention and hydraulic conductivity curves (Section 4.3).

1.5.2 Modelling

A **process model**, Storm Water Management Model (SWMM) of Huber and Dickinson (1995), a **unit hydrograph** (Chow *et al.* 1988), and a **watertable drawdown model** (Youngs *et al.* 1989) were used to model the hydrology of the sugarcane field at the Palmas Site. The watertable drawdown model was used to simulate the soil water processes, in particular the dynamics of the perched watertable. SWMM and the unit hydrograph were used to simulate the field's responses to rainfall. The field data were used to calibrate the models (Section 5.4).

Two sugarcane yield-watertable response models, RC (Rudd and Chardon 1977) and GAYLE (Gayle *et al.* 1987), were coupled to the watertable drawdown model (Youngs *et al.* 1989) to predict sugarcane yield from the watertable dynamics (Section 5.4).

Design criteria were derived from **scenario simulations** within the modelling frameworks. The scenarios were selected to represent the range of climatic conditions recorded in the district over the previous 10 years. They represent the variety of field design possibilities including the role of water furrows in surface runoff and interflow and the consequences of changing the slope and length of the field.

1.6 APPROACH OF THIS THESIS

The study sites, climate, soils, sugarcane cultural practices, and current drainage practices are discussed in Chapter 2. Chapter 3 presents the results of the measurement of the surface flow of water and the depth discharge experiment. The watertable observations and soil hydraulic property determinations are presented in Chapter 4. The watertable, runoff modelling, sugarcane yield measurements and the modelled sugarcane response to excess water is presented in Chapter 5. In Chapter 6 the watertable, runoff and sugarcane yield models are used in conjunction with either long term climate records for the watertable model, or measured rainfall events for the runoff model to formulate improved sugarcane field design criteria for low lying fields.

The data measured for this study are presented on a CD-ROM in Microsoft Excel format at the back of the thesis. Where material is presented in Tables in the Appendix, the Table number is prefixed with “A”.

CHAPTER 2 STUDY AREA

2.1 PHYSICAL CHARACTERIZATION OF RIPPLE CREEK CATCHMENT

2.1.1 Location

The main site of the field research for this thesis, the Palmas Site, is within the Ripple Creek catchment on the north side of the Herbert River. The Ripple Creek catchment is bounded on the west by the Mount Leach Range and Mount Hawkins; on east of the upper catchment by Mount Leach, Gardiner Mountain and South Gardiner Mountain; and on the south by the levees of the Herbert River (Cameron McNamara 1984).

The Palmas Site was located on a commercial sugarcane farm owned by Mr Tony Palmas, in a field approximately 2 km north along Palmas Road, off Hawkins Creek Road (18^{o} 36.038' S 146o 6.032' E) and is 500 m long by 200 m wide (Fig. 2.1). The site was selected, because it had been laser levelled with a slope of 1:792 (**one inch to one chain**), had water furrows included in the field design (14-18 rows between furrows), and had grown sugarcane for approximately 10 years.

A second field site (Lasered Palmas Site) was selected approximately 500 m north west of the main Palmas Site, this field had been laser levelled with a slope of 1:792 but did not have water furrows included in the field design (Fig. 2.1). The field was 500 m long and 200 m wide.

A third field site was located at Macknade Mill (CSR Sugar Ltd) approximately 10 km east of the Palmas Site (Fig. 2.2). The field was divided into 4 experimental plots 35 m wide and 20 m long with two plots having laser levelled slopes of 1:792 while the other two were laser leveled flat (Fig 2.2).

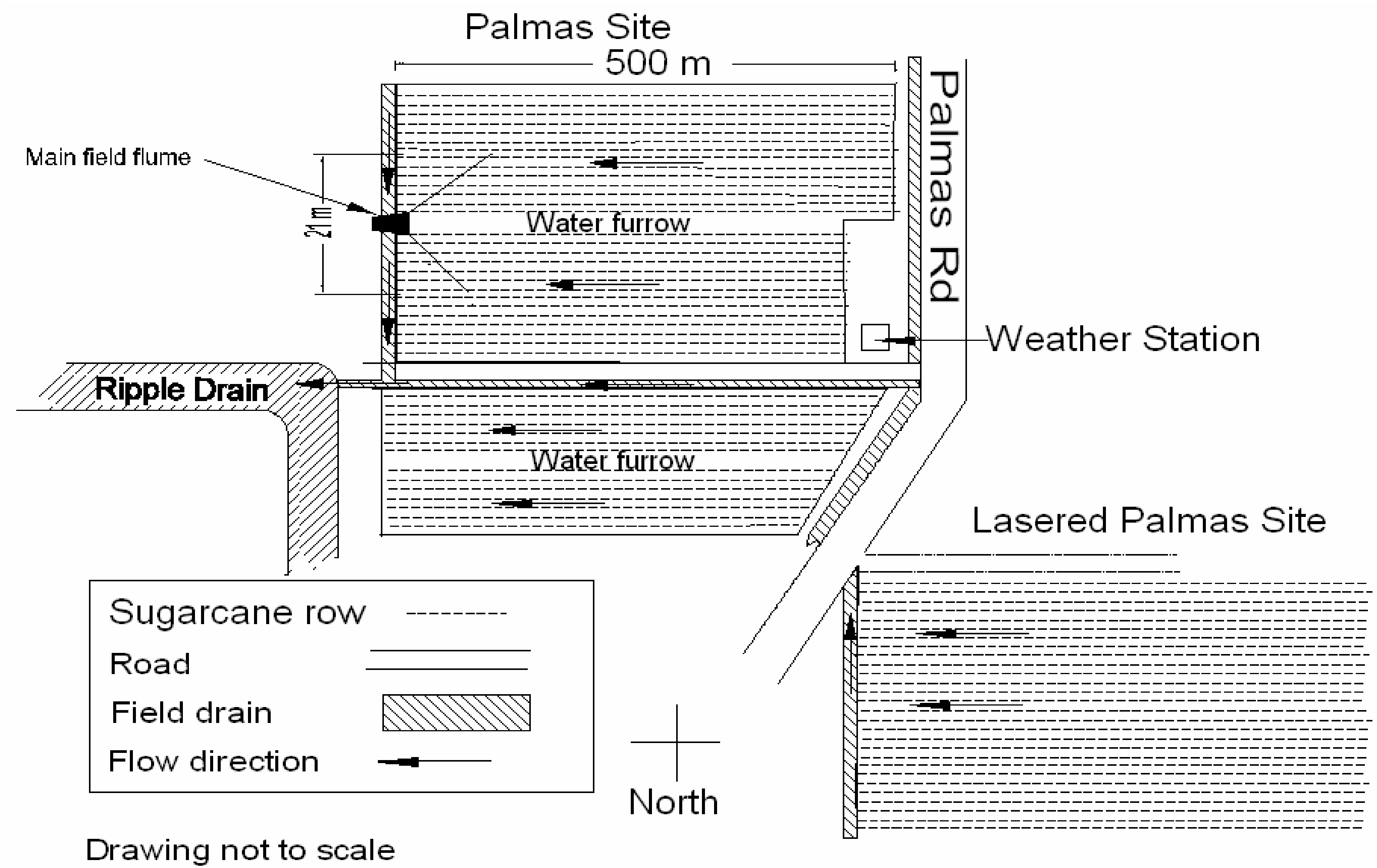


Figure 2.1 Palmas site plan

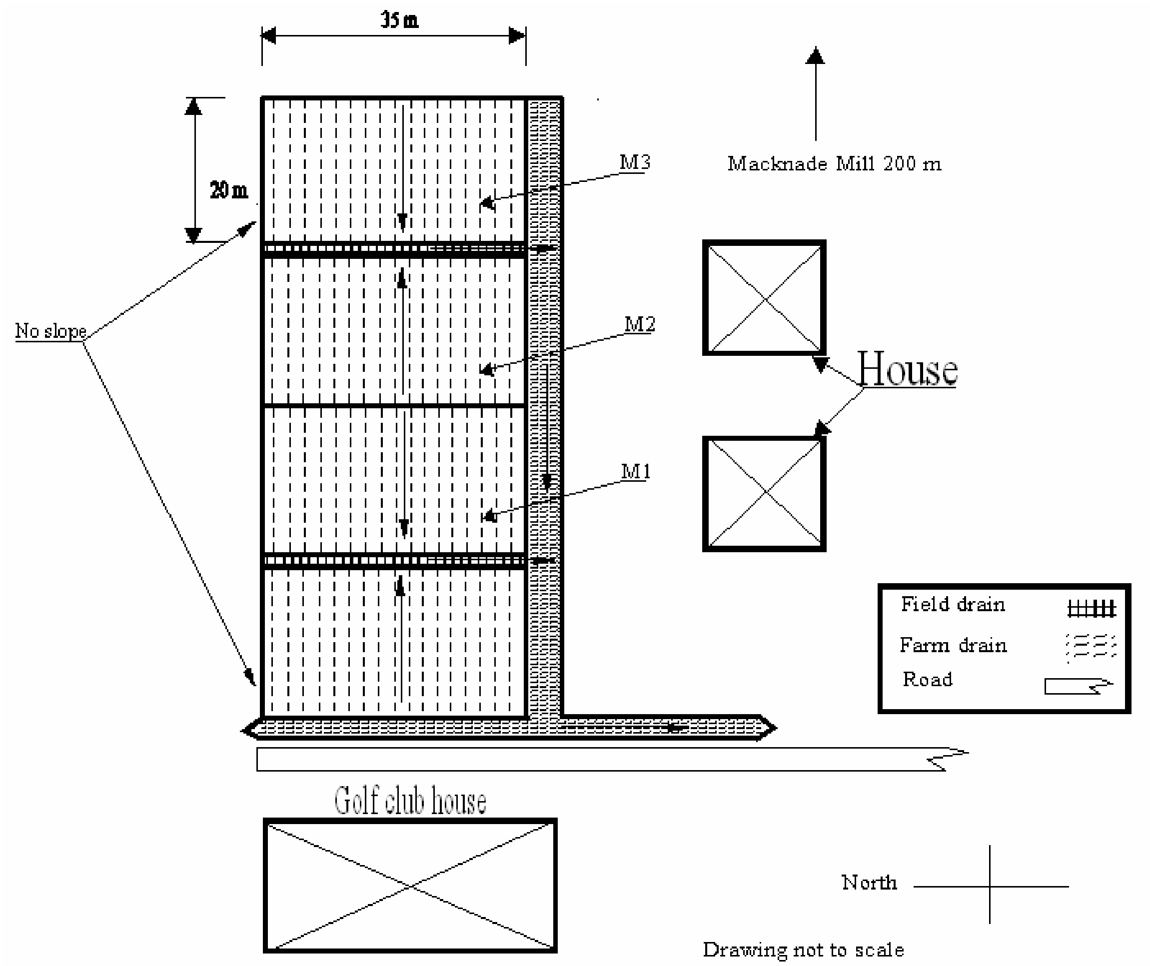


Figure 2.2 Macknade study site plan (Arrows in the field and drain indicate drainage direction. M1, M2 and M3 are the approximate locations of shallow wells).

2.1.2 Climate of the Lower Herbert Valley

2.1.2.1 Temperature

The area experiences warm humid summers and mild dry winters. The mean monthly maximum temperature for the study site is 32 °C during the summer and drops to 25 °C in the winter (Fig. 2.3). Mean monthly minimum temperatures range from 23 °C during summer to 13 °C (Fig. 2.3) in winter and July has the coolest average minimum.

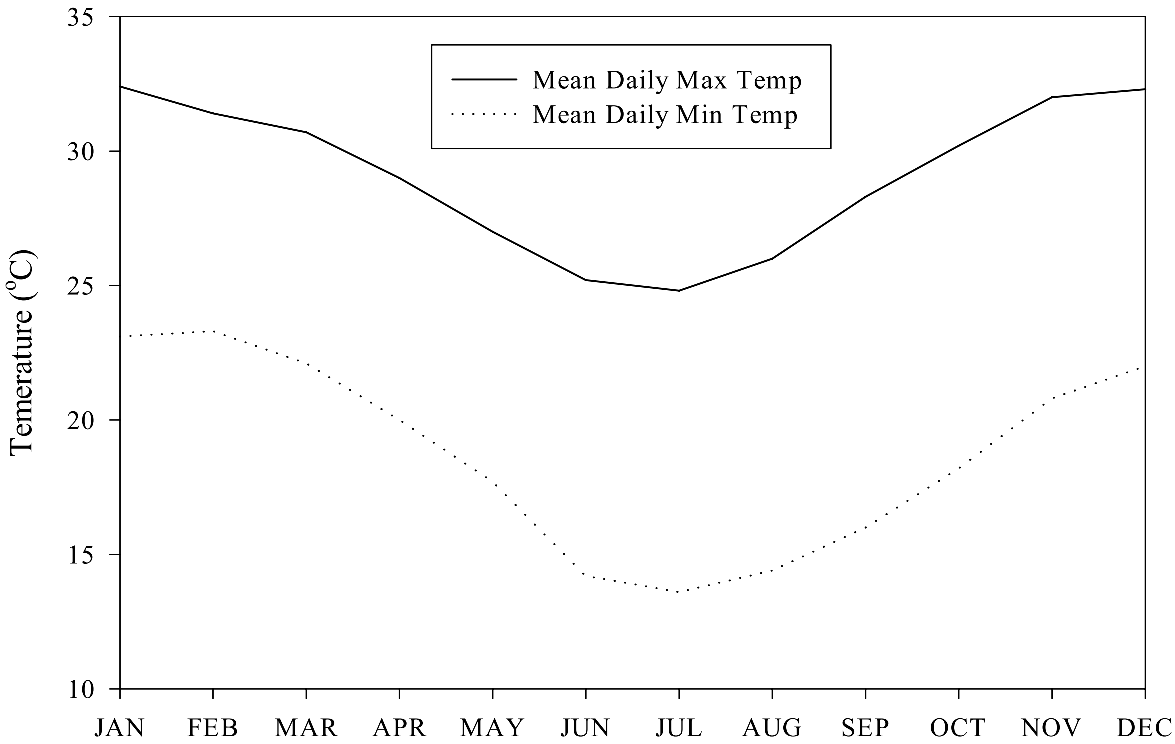


Figure 2.3 Long term (from 1880 to 2000) monthly temperature for Ingham (Bureau of Meteorology 2000)

2.1.2.2 Rainfall

Topography influences rainfall in the area and steep rainfall gradients occur in the Lower Herbert Valley especially near the ranges. Mean annual rainfall for Ingham, the town closest to the study area, is 2069 mm, and exhibits a summer dominated pattern; approximately 80% of the median annual rainfall occurs between December and March (Fig. 2.4). Rainfall variation is significant, the **Decile 9** rain line plotted on Fig. 2.4 shows the 90% probability of the total monthly rainfall being at or below the total indicated, alternatively there is a 10% chance of the monthly rainfall being higher than the total indicated while the Decile 1 line shows the total monthly rainfall having only a 10% chance of not exceeding the indicated total.

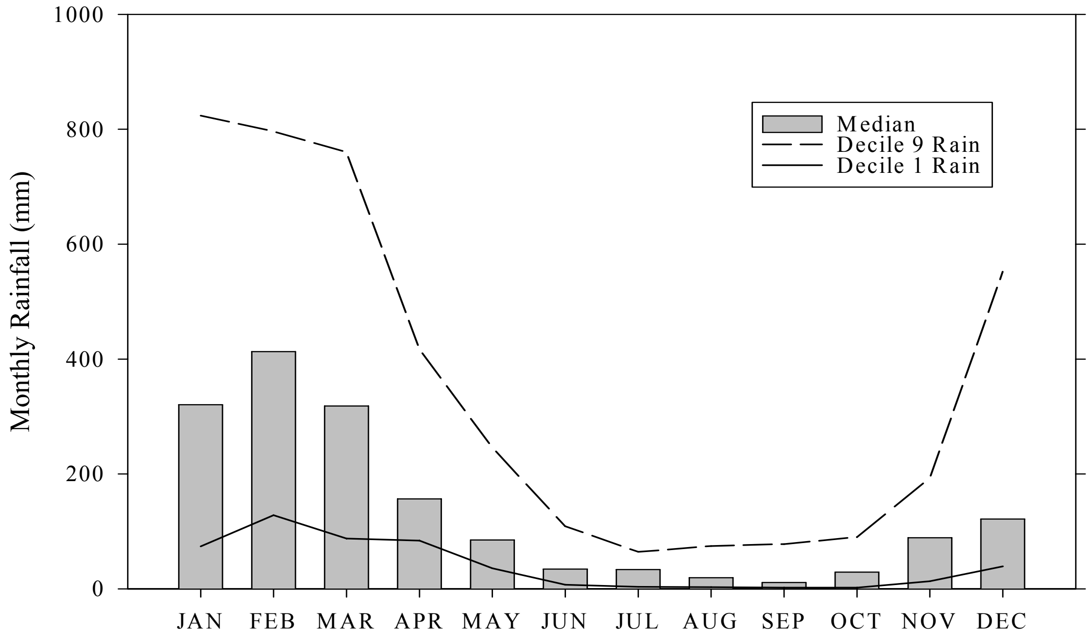


Figure 2.4 Long term monthly rainfall for Ingham (from 1880 to present) (Bureau of Meteorology 2000)

The large rainfall events are driven by the incidence of rare cyclonic events in the wet season. For example in January 1998, Tropical Cyclone Sid produced 323 mm of rain in 24 hours, and 800 mm over a ten day period. No long-term weather data are available for both of the Palmas Sites although an automated weather station was located there from 1993. All the long term climate data used for the Palmas Site was taken from the Bureau of Meteorology weather station at Ingham, and from a weather station at Macknade Mill.

2.1.2.3 Rainfall during the study period

Rainfall was above average in the 1998-99 wet season and well above average for the 1999-2000 wet season (Fig. 2.5). The 1998-99 wet season was long and protracted with above average rain falling in the 1998 dry season and persisting until July 1999 (Fig. 2.5). The 1998-99 wet season was characterized by persistent rain (Fig. 2.5) with twelve separate runoff events being recorded (Section 3.4.2). A major flood occurred on the 12 February 1999 when 159 mm of rain fell in one day. Rainfall during the 1999 dry season was average until November when nearly 800 mm fell in the month.

The **peak rainfall rate** for the 1998-99 wet season was measured as 44.5 mm/hr, this occurred during a rainfall event on 19 January 1999 (Table 2.1). The highest single daily rainfall total was 159 mm on 12 February, while the longest event was 28 hours of nearly continuous rain over the 2 and 3 April 1999.

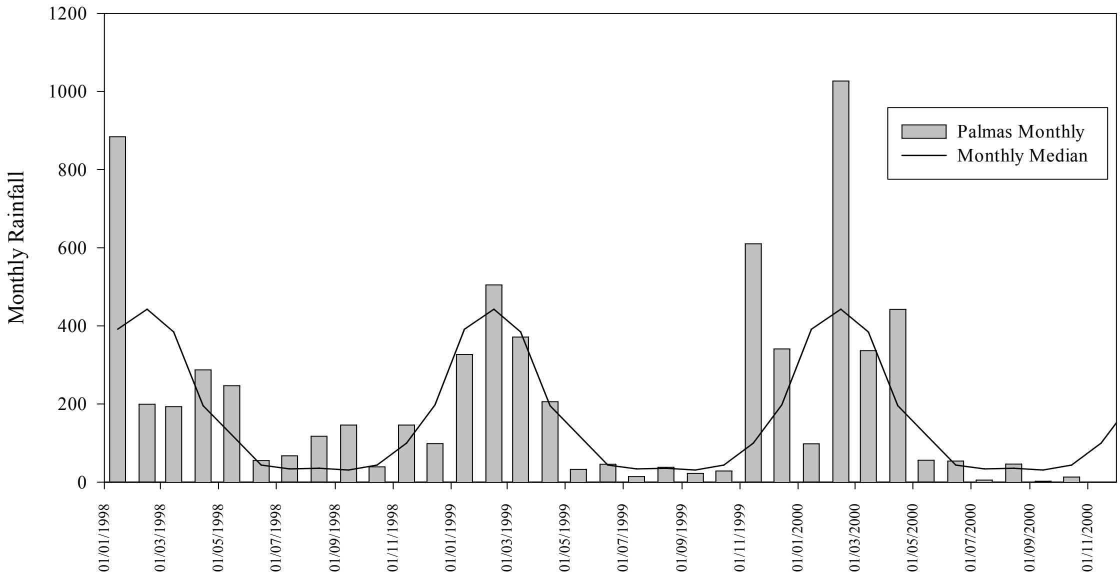


Figure 2.5 Long term annual median rainfall (Bureau of Meteorology 2000) and monthly rainfall at the Palmas Site over the period of the study (1998-2000).

The average peak rainfall for the 1998-99 wet season was 24 mm/hr (median 22.5 mm/hr) and was slightly lower than the corresponding figure of 31 mm/hr (median 32 mm/hr) from the 1999-2000 wet season.

The average rainfall event for the 1998-99 wet season was 71 mm (Table 2.1) which was about half the similar figure of 145 mm for the 1999-2000 wet season.

Table 2.1 Peak rainfall rates, event totals and event durations for runoff inducing rainfall events in the 1998-99 and 1999-2000 wet seasons measured by tipping rain gauge at the weather station at the Palmas Site

Date	Peak rainfall rate (mm/hr)	Rainfall event total (mm)	Duration of rainfall event (hr)
12/12/98	25	74	25.2
6/01/99	21.75	154	22.4
19/01/99	44.5	43	2.6
12/02/99	36.75	160	11.6
15/02/99	21.75	77	2.3
27/02/99	25	56	9.1
6/03/99	17.5	445	20.0
8/03/99	22	61	11.4
9/03/99	12	46	7.8
11/03/99	15	34	6.8
24/03/99	26.25	26	2.8
2/04/99	22.5	76	28.3
Average	24	71	12
Median	22.25	67.5	10.25
4/02/00	60.0	347	43.25
15/02/00	2.5	60	32.75
16/02/00	14.3	60	16.75
18/02/00	3.2	56	32
19/02/00	7.9	66	25.5
25/02/00	18.3	134	40.75
27/02/00	48.9	257	23
9/03/02	59.4	93	20
16/03/00	33.3	231	41.5
Average	145	27	31
Median	93	18.3	32

The 1999-2000 wet season rainfall was very different from that of the 1998-99 wet season, the December 1999 rainfall was slightly above average and January 2000 one of the driest on record. In February 2000, however, over 1000 mm fell which was the highest rainfall on record for that month (Bureau of Meteorology 2000). March rainfall was slightly below average, and April rainfall was slightly above average.

In the 1999-2000 wet season nine rainfall events were recorded that caused runoff (Section 3.4.2). The highest peak rainfall rate was 43.25 mm/hr recorded on 4 February 2000 (Table 2.1) and is similar to the previous wet season highest peak rainfall rate of 44.5 mm/hr (Table 2.1).

The differences between the two wet seasons are apparent from comparing the rainfall event totals throughout the study period. In the 1999-2000 wet season there were four events of over 100 mm compared to two in the previous wet season (Table 2.1). Three of the 1999-2000 wet season rainfall events exceeded 200 mm (Table 2.1). The duration of the events recorded in the 1999-2000 wet season were much longer than those of the previous season. The average rainfall event duration for the 1999-2000 wet season was 27 hours compared to 12 hours for the 1998-99 wet season (Table 2.1).

2.1.3 Hydrology and landforms

The Lower Herbert Valley is a coastal floodplain flanked by mountains with elevations in excess of 1000 m (Fig. 1.2), but commonly 600-900 m with steep slopes (Johnson and Murray 1997). The Ripple Creek catchment is typical of the sub catchments of the Lower Herbert Valley; steep slopes in the upper Ripple Creek catchment remain under native vegetation and the lower flood plain has been cleared for agricultural production. Ripple Creek is the main natural drainage line in the catchment, although artificial drainage lines have been constructed to assist drainage for agricultural purposes. The Ripple Drain was constructed in the 1960s to aid drainage for sugarcane production (T. Palmas pers. comm). Secondary drains were subsequently constructed which flow into Ripple Drain or Ripple Creek. It has been suggested that this greatly enlarged drainage capacity has significantly increased the hydrological responses of the catchment.

The Ripple Creek catchment is divided into two distinct land units; the steep hillslopes that have natural vegetation, and the floodplain that has been cleared for sugarcane production. The floodplain is dominated by low slopes ranging up to 2% and there are old levee banks and alluvial ridges present. Poor land drainage is a significant feature of the Lower Herbert Valley (Wilson and Baker 1990) and the Ripple Creek catchment is no exception. Flooding of the Herbert River and its sub catchments such as the Ripple Creek catchment usually occurs during the wet season with areas behind the levees inundated from the river water and rainfall.

Inundation and waterlogging of sugarcane by rain and flood affects approximately 25 % of the assigned cane area in the Lower Herbert Valley (Tait 1995). In 1997, 4000 ha of the 8565 ha of the Ripple Creek catchment was under sugarcane production. The remaining area was mainly the steep hills and slopes not suited to agricultural production. The Ripple Creek catchment is a typical sub catchment of the Lower Herbert and about 25% of the Ripple Creek catchment may also be similarly affected.

Ripple Creek rises in the northwest of the sub-catchment and flows south then east before emptying into the Herbert River. Ripple Drain begins at the foothills at the western side and drains the south and west before emptying into Ripple Creek in the middle of the catchment.

In 1882 Ripple Creek was diverted from its original course (flowing east towards the Seymour River) and turned southeast towards to the Herbert River by construction of a 4 m earthen embankment across the watercourse (Hinchinbrook Shire Council 1998). The new course was an abandoned river channel, which was deepened and water was diverted southeast to the Herbert River. The Ripple Creek Sugar Mill, now abandoned, used the water for factory operations (T. Palmas, pers. comm.). After storms and prolonged rainfall events, the creek overflows into the old channel, which subsequently flows east into the Seymour catchment, which in turn empties into the Coral Sea. Floodgates were installed at the mouth of the Ripple Creek in 1987 to control outflow to the Herbert River and to reduce the volume of floodwaters that flow back into the Ripple Creek when the Herbert River floods (Cameron McNamara 1984). Before installation of the floodgates reverse flows from the Herbert River at heights of 7.28 m above **Australian Height Datum** (AHD) contributed significantly to flooding around the mouth of Ripple Creek (Cameron McNamara 1984).

2.1.4 Soils of the Ripple Creek catchment

The Ripple Creek soils have been described in three studies:

a land suitability study (Wilson and Baker 1990) of all of the sugarcane producing soils within the Herbert Valley at a scale of 1:100 000;

a land capability study (Wood 2002): limited to parts of the Lower Herbert Valley at a scale of 1:5000; and,

a map of hydrological properties (Timmer 1998) confined to the soils of the Ripple Creek catchment. The study by Timmer (1998) measured the hydrological properties of the key soil types, as defined by Wilson and Baker (1990), present in the Ripple Creek, and combined the soil hydrological properties and position in the landscape into what were termed **pedo-hydrological units**.

2.1.4.1 Land suitability study of Wilson and Baker (1990)

The land suitability study (Wilson and Baker 1990) divided the landscape into 4 broad groups:

- River alluvial

The soils of this group consist of the alluvial material that has been deposited from recent flood events in the Herbert River and display a range of profile characteristics. The soils are described as predominantly of gradational **principal profile form**, and the textures varied from sand to silty clay loam in the A horizons to fine sandy clay loam to medium clay in the B and C horizons. Soil development is variable and principal profile forms range from weakly gradational to weakly **duplex**. The soils have high permeability and well drained.

- Alluvial plains

The soil group is typical of a floodplain catenary sequence, with lighter textured soils dominating the levee ridges close to streams and heavier textured soils further away on the floodplains. The near-levee soils are light textured, well drained, with gradational principal profile forms, while the far-levee soils are largely **texture-contrast** clay soils with low permeability and poor drainage. The Palmas Site is located within the group of far-levee soils. The dominant principal profile form is duplex soil with a silty loam topsoil overlying light to medium clay subsoil. The far-levee soils are widespread and form the largest single group of soils within the Ripple Creek catchment, and are the most important for sugarcane production in the sub catchment.

- Creek alluvial

This group of soils follows a similar catenary pattern to the alluvial plains described above with bleached duplex soils predominant. The flat topography of the creek alluvial plains lacks the developed drainage lines of the river alluvial plains and the soils follow the typical floodplain development of lighter textured soil on the ridges and heavier textured soils on the back slopes.

- Hill slopes

These soil types are derived from the granite and acid volcanic hills. Sediment eroded from hills form **colluvial fans** at the base of the hills. The soils have gravelly A horizons with the soils at the lower part of the fan having sandy clay to medium clay B horizons. The soils lower in the sequence are typified by imperfect internal drainage.

2.1.4.2 Pedo-hydrological units

Timmer (1998) sampled the major soil types of the Ripple Creek catchment, based on the land suitability study (Wilson and Baker 1990). This study then classified the soils on the basis of saturated hydraulic conductivity and grouped the soil into three nominal permeability classes, high, medium, and low (Fig. 2.6). This soil classification allowed the probability of runoff, inundation, and waterlogging to be calculated.

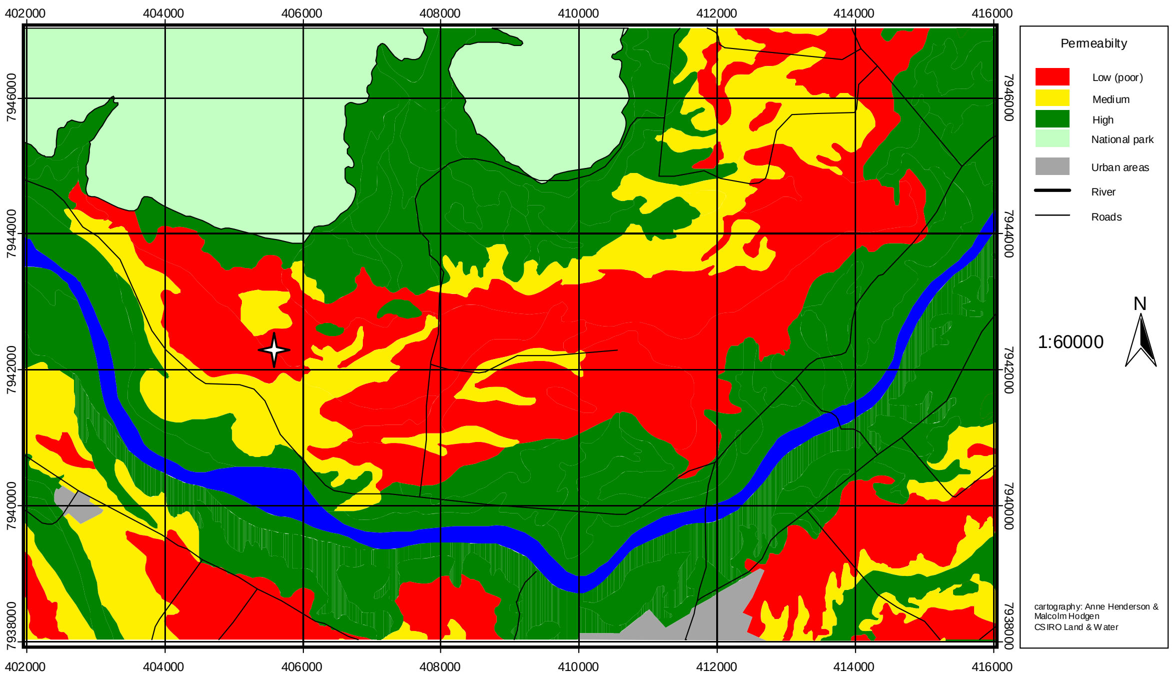


Figure 2.6 Pedo-hydrological units of the Ripple creek catchment (Timmer 1998) Dark green is high permeability, yellow is medium permeability, and red is low permeability. Both Palmas Sites are indicated by ✧ symbol. Macknade site is not shown.

2.1.5 Soils at the experimental sites

2.1.5.1 Palmas Site

The soil at the Palmas Site has a dark grey silty clay texture A1 horizon, with a cracking surface, neutral pH trend, and a weakly developed A2 horizon. The B horizon is strongly mottled grey light clay that grades to a mottled yellow brown heavy clay C horizon, and a yellow brown sandy D horizon below 1.4 m (Table 2.2 and Fig 2.7). The soil has been classified as a Kurosolic Redoxic Hydrosol (Isbell 1996; S. Eldridge, pers. comm.), and as a Hamleigh/Toobanna soil type (Wilson and Baker 1990). The principal profile form is described as Dy3.41- Dy3.43 (Wilson and Baker 1990).

Table 2.2 Soil profile description from soil pit dug at main Palmas site April 1999. Soil described by S Eldridge Munsell colour codes are for moist soil

Layer	Horizon	Depth (m)	Description
1	A	0-0.40	Dark grey (10YR 3/2); silty clay loam; sub-angular blocky, dense root growth
3	B	0.40-0.95	Yellow brown (matrix colour 10YR 5/2, mottles 10YR 6/8); medium clay; sub-angular to angular blocky, no roots
4	C	0.95-1.40	Yellow brown (matrix 10YR7/2, mottles 10YR6/8); heavy clay; massive to angular blocky
5	D	1.40-	Yellow brown (10YR7/1, mottles 10YR5/8); sandy loam; massive.

Figure 2.7 Soil profile from Palmas Site (blue marks on the tape are at 200 mm intervals)

2.1.5.2 Palmas Lasered Site

The soil at Palmas Lasered Site was described in January 2000, when two holes were hand augered to a depth of 1.0 m for installation of shallow wells (Section 4.3). The surface soil at both holes was similar to the Palmas Site soil, a dark grey, silty clay textured with a cracking surface. The soil from the hole augered at the top of the field was similar to the soil described above in Table 2.2. However the soil from the hole at the lower end of the field was a dark grey, silty clay with a sharp horizon change at 0.4 m to a heavy yellow brown clay similar to the C horizon described in Table 2.3. The soils from both holes were classified as a Kurosolic Redoxic Hydrosol (Isbell 1996; S. Eldridge, pers. comm.).

2.1.5.3 Macknade Mill Site

The soil at the Mackande Mill site was described by Wilson and Baker (1990) as a hardsetting silty clay loam A horizon soil grading into a fine sandy loam C horizon, a neutral pH trend, with a principal profile form of Um7.11 to Um6.3 (Table 2.3). The soil has been classified as a Leptic Tenosol/ Stratic Rudosol by S. Eldridge (pers. comm.).

Table 2.3 Soil profile description of Macknade soil type (Wilson and Baker 1990)

Layer	Horizon	Depth (m)	Description
1	A1	0-0.45	Dark brown to grey brown (5YR 3/1, 4/2); silty clay loam; weak to strongly developed 5-10 mm blocks, visible roots.
2	C	0.45-1.20	Brown, yellow brown (7.5YR 4/3,); sand to fine sandy loam; apedal.

2.1.6 Vegetation of the Ripple Creek Catchment

The vegetation of the Ripple Creek Catchment is divided into two distinct areas: the hills and slopes too steep to pursue agricultural production that still is under native vegetation of mainly rainforest species; and the floodplain that has been cleared and is nearly a monoculture of sugarcane.

The original vegetation on the floodplains was a variety of tea tree species (*Melaleuca spp.*) (Johnson and Murray 1997). This was cleared during the first half of the 20th century to make way for increased sugarcane production (Johnson and Murray 1997). There are only relatively small areas (< 100 ha) of natural vegetation left on the Ripple Creek flood plain (Johnson and Murray 1997).

2.2 SUGARCANE CULTURAL PRACTICES OF THE LOWER HERBERT VALLEY

Sugarcane is a grass and belongs to the family Poaceae. All of the varieties of sugarcane grown today are crosses from the noble cane *Saccharum officinarum* L. and various other species *S. sinense, S. barbari, S. robustum,* and *S. spontaneum* (Rehm and Espig 1991). For optimum growth, sugarcane requires an average temperature of 25-27^{0}C, and 1500-1800 mm of water (Rehm and Espig 1991).

The Lower Herbert River district has approximately 60, 000 ha of land under sugarcane that supplies two sugar mills (CSR Sugar Victoria and CSR Sugar Macknade). Sugar is the largest intensive agricultural industry in the Lower Herbert catchment. The Ripple Creek Catchment supplies the Macknade Mill (Johnson and Murray 1997). The average long term cane yield per harvested area is 77 t/ha for the Victoria Mill area and 72 t/ha for the Macknade Mill area compared to a long term average of 88 t/ha for all of Queensland (J. Rehgenzani, pers. comm.). The average long term commercial cane sugar content (**CCS**) for both mills is 13.5% (J. Rehganzani pers. comm.). The average long term sugar yield for both mills is 10.2 t **94 net titre** sugar/ha (J. Rehganzani pers. comm.). Sugarcane is typically grown on family-owned and operated farms of about 60-100 ha. While most farmers in the Lower Herbert Valley produce on average about 7, 000 t or less, several farmers have individually produced in excess of 15, 000 t of cane annually (Canegrowers 1999).

Sugarcane production in the Lower Herbert Valley is based on a system of **green cane trash blanket** harvesting and minimum tillage with an average crop cycle of 5 years. The cane is planted in the first year into a ploughed field, is harvested and allowed to ratoon. This cycle is repeated annually for usually 4 years, in the final year the field is ploughed out, and either fallowed or replanted. The majority of the cane crop is planted in June and July, with the planting season ranging from April to September. This first phase of the crop cycle is called the plant cane, and subsequent crops are referred to as first ratoon, second ratoon, etc (Canegrowers 1999).

2.2.1 Agronomy of sugarcane

Sugarcane is grown by vegetative propagation of sections from stem of mature cane, called setts. The plant cane setts contain two or more eyes or nodes (growing points) and are planted in rows 1.5 m apart. The setts are planted 1 m apart along the row by **whole stick planters** or **billet planters**, which use pre-cut cane **billets** from the harvester. The planter forms a furrow, cuts the mature cane stalks into setts of about 250 to 300 mm (whole stick planter), or precut billets for a billet planter, treats them with fungicide, adds fertiliser (and sometimes insecticide) and plants them 10 mm deep in the planting row. After emergence, usually around 3-6 weeks after planting, the rows are **hilled up** by moving soil from the inter row to the row. The hills are usually about 100 mm high and 750 mm wide. During early growth of the plant cane some tillage, usually a light harrowing, is performed for weed control; final tillage for weed control is undertaken around November (Canegrowers 1999). Each sett produces a stool of about 8-12 cane stalks.

Sugarcane requires high inputs of nitrogen fertilizer and this applied usually to the soil surface or is banded next to the stool as urea in November-December. Sugarcane has requirements for other nutrients such as phosphorus, potassium, and sulphur that are applied as a granular mix with the nitrogenous fertilizer. The typical fertilizer mix for plant cane is N:P:K:S 150:25:80:20 kg/ha and for ratoon cane N:P:K:S 200:20:100:20 kg/ha (Canegrowers 1999). The crop is sprayed for weeds in December usually just before canopy closure. Pests are a major threat to sugarcane. These include cane grubs, wireworm, nematodes, and rats. Sugarcane is susceptible to diseases, which include, ratoon stunting disease, pineapple disease, rusts and smuts. Due to the trash blanket, usually no interrow cultivation is undertaken after the first harvest (Canegrowers 1999).

2.2.2 Harvest

At harvest the cane stands 2-4 m tall, is 11-18 months old, and is green (not burnt). Harvesting commences towards the middle of June and usually continues to late November or December. The quality of the juice extracted from the cane peaks around September then declines slowly to November and then rapidly (Canegrowers 1999). The grower is paid for the sugarcane delivered to the mill on a formula that combines the tonnes of sugarcane produced and the **ccs** of the cane juice. The mill determines the content of sugar in the juice by measurement of the polarity of the juice (**pol**) and the impurities of the juice by a measure of all the dissolved material (**brix**). Due to the seasonality of the ccs, the mills normalize the ccs using the **harvest season average** to even out the seasonal effects on payments to the growers (Canegrowers 1999).

All commercial sugarcane in Australia is harvested by self-propelled, mechanical harvesters (Canegrowers 1999). The harvesters travel along the rows of sugar cane stalks, cutting one row at a time just above the soil surface, discharging the sugarcane leaf and green tops out of the harvester, the stalks are cut off at ground level and chopped into small lengths called billets. These are loaded into bins along side the harvester, the bins are either self propelled or towed by a tractor. The bins are taken to a tramway siding for transport to the mill. The haul out bins range in size from approximately 1 t to 9 t. After harvest, the base of the plant left behind grows new shoots that produces the ratoon crop. Three to four ratoon crops are usually grown before the land is fallowed (or planted with an alternative crop such as legumes), or ploughed and replanted to start the cycle again (Canegrowers 1999).

2.3 CURRENT DRAINAGE PRACTICES

2.3.1 Surface drainage

Surface drainage has been a major factor in sugarcane field design in the wet tropics. The Bureau of Sugarcane Experimental Stations (BSES), CSR Sugar Ltd., Herbert River Protection and

Productivity Board (HRPPB), and local contractors have developed drainage guidelines for laser grading of sugarcane fields within the Herbert Valley due to the demand by growers for guidelines to improve productivity. The main criterion the designers incorporate into the field design is to remove surface water while minimizing the amount of soil to be moved in the laser grading operation.

A review of the field designs for land forming in the Lower Herbert Valley was compiled by Park (1999). Land grading practices started in the Herbert Valley in 1975, with the purchase by a local contractor of two land planes. The HRPPB purchased a laser land plane in 1980 and survey laser and software to estimate cuts and fills in 1991; two laser rigs with improved surveying software were subsequently purchased in 1997 (D.Horsley, pers. comm.).

The following is a collation of information from the literature and conversations with David Horsley (Victoria Mill, CSR Sugar Ltd.), Rick Beattie, John Rehgenzani, Greg Shannon (BSES Ingham), and Ron Kyrkwyk (HRPPB).

2.3.1.1 Slope

Slope of a field is described in terms of the down slope and **cross slope** components, where the down slope is the slope along the length of the field and the cross slope is the slope across the width of the field (Fig. 2.8). The cross slope is sometimes called **alternate slope.**

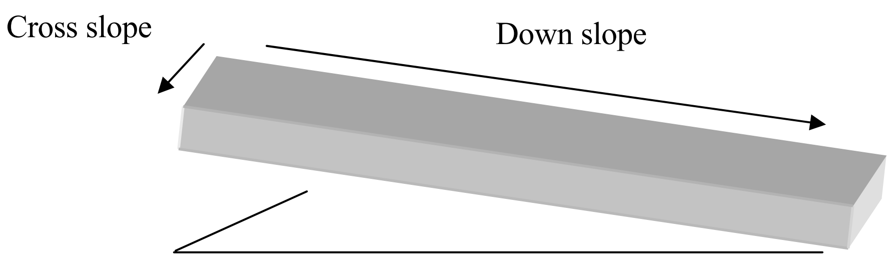


Figure 2.8 Sketch of a field showing slope components lines at the bottom represent the horizontal

Slopes of fields should be between 0.05% and 1% (Kingdon 1991), or 1:792 (one inch per chain) as a minimum slope, or as near to the natural slope as possible. In practice the average down slope (slope along the length of the field) was found to be 0.49 % with 2300 field designs in the Lower Herbert Valley or 88% of the field designs having a down slope of between 0.05-1% (Park 1999).

The artificially produced down slope of fields in the Lower Herbert Valley were dependent on the soil type present in the field. Park (1999) found the majority of the fields (61%) that were laser levelled were located on the alluvial plains, and of those 23% had a down slope greater than 1% (Park 1999).

The criterion for laser levelling sugarcane fields is to limit the amount of soil to be moved to less than 250-300 m^3/ha. The criterion for the slope is determined by "working with the land" by forming the field using the *in situ* slopes as a guide, and limiting the amount of soil to be moved (R. Beattie, pers. comm.; D. Horsley, pers. comm.). In practice, the average volume of soil cut was 299 m^3/ha (Park 1999) and 46% of the fields had more soil moved than the recommended amount (Park 1999).

2.3.1.2 Field drains

The typical design recommended by the HRPPB and CSR Sugar Ltd was for field drains to be 2.5 m wide at the base, 0.25-0.5 m deep, and the side slopes to have batters of 8:1 or flatter. In principle the drain design is set by the laser grading machinery dimensions with the drains as wide as the laser scoop (2.5-3 m) and about 0.3 m deep (R. Beattie, pers. comm.). Cross drains are drains that run across the width of the field and are usually dug 0.3 m deep. Cross drains (Fig. 2.9) are a recommended feature, however producers cite accessibility problems with these structures as they sometimes have difficulty moving farm machinery across them.

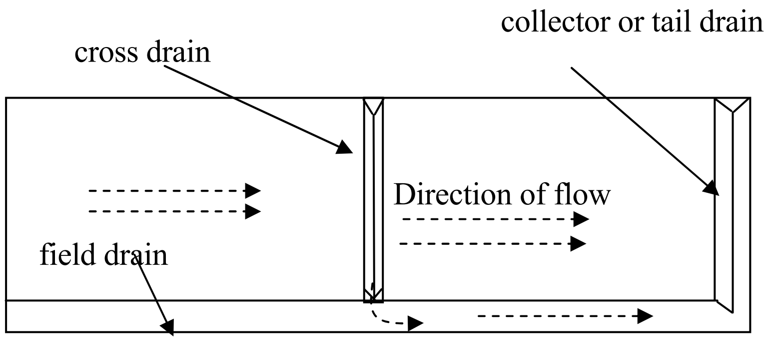


Figure 2.9 Schematic diagram of field drain types and flow direction (shown by dotted lines)

2.3.1.3 Water furrows

Intra-field drain (water furrows) (Fig 1.3) spacing is set at every 14-18 rows in the field due to historical practice. This is a remnant of the hand harvesting system in which the two rows of sugarcane were cut and laid into a third cut row. The cane stalks were collected into bundles and loaded on to flat top wagons that ran along temporary tramlines placed in the water furrows. Therefore, the cutters only had to move the bundles of cane a maximum of 8 rows. Internal drainage designs subsequently developed using the water furrow as a surface flow interception structure.

The efficiency of the drain is thought to be improved by bedding the cane into a **polder type design**. (J. Reghenzani, pers. comm.; D. Horsley, pers. comm.) The polder design relies on moving the soil from the water furrow towards the centre of the beds. The elevated bed creates a gradient for water to drain from the soil.

Water furrows are usually eliminated after the field is laser graded, but some farmers still laser grade and re-install water furrows. There are no data on the number of fields in the Lower Herbert Valley that still have water furrows.

2.3.1.4 Interrow distances

Interrow (drill) distance is 1.52 m (5 feet) and is inherited from historical practices. Originally cane was planted in rows 1.37 m (4 feet 6 inches) apart, as this was twice the maximum width of a single mouldboard plough furrow. The row was ploughed in one direction which moved the soil on to a row. Then the other side of the row was ploughed, moving the soil in from the other side to form a mounded row.

With the advent of mechanization, the rows expanded to 1.52 m, however research is continuing into the optimum row spacing. The current distance is regarded by many as too narrow for effective machinery operations (J. Reghenzani, pers. comm.), or too wide for maximum production (Bull 1999).

2.3.1.5 Field length

The field length is determined by a number of factors. If there is a current internal field drain in the farm design then the field is designed to fit the current dimensions of the drains. In some cases the length of the field is determined by estimating the length of row required to fill one bin at harvest (D. Horsley, pers. comm.). In 1999 it was decided that maximum length of a continuous slope in the **Herbert River Productivity and Protection Board** area would be 300 m: a cross drain would be inserted into the design at that distance (G Shannon, pers. com.). This recommendation was to assist drainage by allowing water to flow off the field in an attempt to ease inundation.

2.3.1.6 Drain density

An extensive survey of all the drains in the Ripple Creek catchment was completed in 1999 (Reghenzani and Roth 1999). From this study the current field **drain density** was determined at 0.15 m/m^2.

2.3.1.7 Field size

Field size has not been considered as part of the design criteria although a modulus of drainage of 5 L/s/ha is the accepted figure (Cameron McNamara 1984). The current average field in the Lower Herbert Valley has an area of 4.98 ha with the range between 0.14 and 30 ha; 97% of the laser fields were sized between 0.14 ha and 15 ha in area (Park 1999).

2.3.2 Sub surface drainage

Sub surface drainage within the Lower Herbert Valley began in 1976, mainly as solution to "troublesome wet spots" (Horsley *et al.* 1982). In 1982, 260 ha in the Lower Herbert was drained by **tile drainage** (Horsley *et al.* 1982) and the effect of the installation of subsurface drainage was in general an increase in yield from 88% of the mill average before installation compared to 105% post installation (Horsley *et al.* 1982).

Typically a trench was dug every 20 m along the down slope to a depth of 1 m using a Donley drain digger. Perforated flexible pipe 100 mm in diameter was laid in the drain and backfilled with coarse sand and gravel (D. Horsley pers. comm.). Another study suggested the drain spacing required to provide effective drainage was 8-15 m (Ridge and Reghenzani 2001), however there was no systematic approach to determine the drain spacing and drain depth (D. Horsley pers. comm.). The very low soil hydraulic conductivities of the clay B horizon required very close drain spacing (Ridge 1980) and made the systems too expensive to install (D. Horsley pers. comm.). In addition, the required fall on the sub surface drains would make the drainage outfall too deep for effective use. (R. Beattie, pers. comm.; D. Horsley, pers. comm.)

Mole drains were also trialed with different design layouts installed on low lying sugarcane fields. Herringbone patterns of mole drains were formed down each interrow and sand filled mole drains were all trialled (D. Horsley, pers. comm.). The main drawback was the apparent ineffectiveness of the drains on productivity, there was no appreciable increase in sugarcane yield, (D. Horsley, pers. comm.). It was found through trial and error that the drain spacing had to be in each interrow space to be effective but this was too expensive to be implemented (T. Palmas, pers. comm.). The moles drains collapsed internally and were replaced by sand filled mole drains (T. Palmas, pers. comm.). The sand filled mole drains appeared to work ("they seeped all the time" T. Palmas, pers. comm.) but again they were too expensive to justify due to the close spacing, the sand fill, and the installation time (T. Palmas, pers. comm.).

In 2000, BSES undertook a mole drainage trial located on the field adjacent to the Ingham BSES office on a representative low lying sugarcane field. Where a sand filled mole drain was formed from the headland to about 2-3 m into the field at a 45^{o} angle every 1.5 m (J. Reghanzani, pers. comm.). The initial results showed a visible increase in the growth of the sugarcane plant (J. Reghanzani, pers. comm.).

CHAPTER 3 INUNDATION

3.1 INTRODUCTION

Inundation of low lying sugarcane fields is the most visible symptom of inefficient surface drainage and poor field design. In this chapter, the hydrological processes that lead to inundation are discussed, and the causes of inundation are identified. Runoff from studied fields were measured and modelled, and a **water balance** for the Palmas Site was developed.

Inundation of sugarcane in the Lower Herbert Valley has been managed historically by field design with water furrows originally included to remove excess water to overcome inundation (Section 1.2). The current practice is for the field to be laser levelled to allow drainage and remove low areas where excess water may pond. Water furrows may be retained to remove excess water or the field is land shaped and the water furrows removed. The inclusion of water furrows in the field design may increase the hydrological response of the field to rainfall and hence that of the whole catchment. The increased hydrological response may exacerbate inundation for fields further down the catchment. The hydrology of the water furrows within the field is examined in this chapter and rate and volume of runoff from fields determined.

The current field design criteria with or without water furrows (Section 2.3), have arisen from the experience of the local field designers and laser levelling contractors. There is no requirement on the designers to maximize crop productivity or to optimize the discharge of the fields to manage the drainage water across the whole catchment.

3.1.1 Approach of this chapter

In this chapter, the physical processes involved in inundation are explored. The interaction between inundation and crop response is dealt with in Chapter 5.

Surface drainage can be described as overland flow which is defined by Ritzema (1994) as "Water flowing over the soil surface towards rills, rivulets, channels and rivers". Overland flow is discussed as surface drainage within the context of the present study.

Surface runoff was measured from the study sites, the evidence for the type of overland flow (**saturation excess**) is presented (Section 3.4.5), as well as evidence that the flow regime of the runoff is **submerged flow** (Section 3.4.2). The surface water balance of the field was developed by partitioning surface runoff between down slope flow through the water furrow and down slope flow from the sugarcane rows (Section 3.4.3). This aids in the identification of the influence of the water furrow on runoff of the field.

3.2 THEORETICAL BACKGROUND

3.2.1 Surface water balance

All the water that falls on the field must be accounted for in a mass water balance. The surface of the field can be conceptualized as a two dimensional plane, water enters the plane as rainfall, and is removed by infiltration or runoff, in this case evaporation and evapotranspiration is ignored due to the relatively short timescale (usually less than 24 hours). Runoff is either from the row or from the water furrow.

The components of the water balance can be identified in the following relationship:

$$R = Ru + I \qquad \text{Equation 3.1}$$

Where
R is rainfall (mm)
Ru is depth of runoff (mm)
I is the depth water that infiltrated the soil (mm)

The runoff can be partitioned in a field with water furrows between the volume of water that runs off the field via the water furrow and the volume of water that drains from the field via the rows.

Rf= RR+WFR Equation 3.2

Where
Rf is the depth of runoff from the field (mm)
RR is the depth of runoff from the row in the field (mm)
WFR is the depth of runoff from the water furrow in the field (mm)

3.2.2 Flow generation

The generation of overland flow starts when the precipitation rate exceeds the infiltration rate of the soil and the soil becomes saturated, water ponds on the soil surface, and flows according to the slope and roughness of the soil. The flow type of the overland flow will reflect the hydrology of the soil. Two specific types of flow can occur; saturated excess or **rainfall excess** (**Hortonian**) flow (Moore and Foster 1990). If the whole profile is saturated then the former will occur. If a surface soil crust is present, or if the precipitation rate is higher than the saturated soil hydraulic conductivity, then rainfall excess flow will occur (Moore and Foster 1990).

The movement of water overland can be described as sheet or channel flow. Sheet flow occurs when the water is not concentrated into channels and moves over the surface in a shallow sheet, channel flow occurs when the water collects in small depressions and then into small rills and gullies and moves down slope feeding into successively larger drainage lines.

3.2.2.1 Saturated overland flow

Saturated flow occurs when the soil is fully saturated and further precipitation leads to additional water draining from the surface as overland flow. The mechanism for saturated overland flow can be conceptualised as the watertable rising to intercept the soil surface causing

exfiltration (Moore and Foster 1990). Therefore the factors that control the dynamics of the watertable will have a direct impact on the overland flow process. These factors include the depth to the soil layer that impedes the internal drainage and causes the soil water storage capacity to be exceeded, which in turn creates a watertable; the antecedent soil moisture content determines the amount of rain required to saturate the soil profile and cause overland flow.

3.2.2.2 Rainfall excess overland flow

Rainfall excess overland flow occurs when the rainfall intensity exceeds the hydraulic conductivity of the surface soil, and the excess water runs off. This type of flow requires that there be an unsaturated zone just below the soil surface, and that the soil removes water from the overland flow at a rate governed by the hydraulic conductivity of the soil surface. If there were no unsaturated zone, then this would be saturated overland flow. The soil may develop a surface seal, which restricts the infiltration of the water into the soil to less than the measured hydraulic conductivity.

3.2.3 Flow regime

After the generation of overland flow, the water is concentrated into channels, and if that water encounters no impediments it is termed **free flow**. Free flow can be defined as the flow in a channel which is not affected by the level of the **tail water** (Moore and Foster 1990). Free flow is more precisely defined by the Froude number which is the ratio between inertial forces and the gravitational forces:

$$Fr=V^2/gh \qquad \text{Equation 3.3}$$

Where
Fr is the Froude number
V is the velocity of the water (m/s)
g is the acceleration due to gravity (m/s^2)
h is the depth of water (m)

When the Froude number is equal to one, the flow is termed critical flow and the discharge at this flow regime is uniquely related to the depth of the flow. If the Froude number is greater than one the flow is termed supercritical. When the Froude number is less than one, the flow is termed subcritical and disturbances downstream propagate upstream and affect the flow.

3.2.4 Resistance to flow

Low angle slope and the resistance to flow created by the thick trash blanket are the key features of the sugarcane fields in the Lower Herbert Valley. The resistance to flow is the measure of force resisting the flow of water against gravity (Moore and Foster 1990) and this can take the form of the Darcy-Weisbach resistance equation (Moore and Foster 1990):

$$u = \left(\frac{8g}{f}\right)^{\frac{1}{2}} R_0^{\frac{1}{2}} S_b^{\frac{1}{2}} \qquad \text{Equation 3.4}$$

Where
u is the mean flow velocity (m/s)
g is the acceleration due to gravity (m/s^2)
f is the friction factor (dimensionless)
R_0 is the hydraulic radius of the channel (m)
S_b is the bed slope (m/m)

The factor *f* is usually determined as a function of the **Reynolds number** of the flow and a parameter describing the roughness of the flow path (Moore and Foster 1990). Smith *et al.* (1990) reported that many unsuccessful studies have been conducted to determine relationships between *f* and vegetated surfaces. However, empirical relationships which include resistance terms such as those developed by Horton (1938), by the Manning’s equation, and by the Chêzy equation have been used successfully to determine the flow rate (Moore and Foster 1990).

The Mannings equation was developed to relate open channel flow to the slope and depth of water in the channel. A factor was introduced (Moore and Foster 1990) to account for the resistance experienced by the flow. such that:

$$q = \frac{y^{\frac{5}{3}} S_e^{\frac{1}{2}}}{n}$$ Equation 3.5

Where
q is the discharge (m^3/s)
y is the depth of flow (m)
S_e is the **energy slope** (m/m)
n is the Mannings coefficient of roughness (dimensionless)

Turner *et al.* (1978) developed a simple depth discharge relationship that is similar to Manning's equation however it groups the resistance term with the slope:

$$q = K_h y^m$$ Equation 3.6

Where
q is the discharge (m^3/s)
K_h is a coefficient (L/s)
y is the depth of flow (m)
m is the exponent

The disadvantage of showing the generalized depth discharge equation this way is that slope is not explicit in the formula. The equation can be rewritten as

$$q = \varsigma y^{\alpha f} S_e^{0.5}$$ Equation 3.7

Where
q is the discharge (m^3/s)
ς is a flow coefficient (L/s)
y is the depth of flow (m)
S_e is the energy slope (m/m)
αf is the exponent of depth of flow and takes on the following values: 0.5 for turbulent low, 1 for laminar flow, 0.5-1 for mixed flow.

It has been proposed by Smith *et al.* (1990) that flow through dense vegetation is not well described by the Manning equation (Equation 3.5) because such a flow is fully turbulent and the viscous forces of the water exerted on the channel are considered to be negligible. But when water moves through thick vegetation, the viscous forces exerted on the vegetation may dominate and increase the hydraulic resistance of the flow (Mahashwari 1992).

Raine *et al.* (1997) using Manning's equation, modelled surface irrigation water flowing on low angle slopes over sugarcane with no thick trash blanket. This study used Manning's equation to describe the resistance to flow and reported a range of measured Manning's n between 0.07-0.15 for such flows (Raine *et al.* 1997).

Manning's equation appears to be valid for low angle slopes it has not been tested for low angle slopes with a thick trash blanket. To test the ability of the Manning's equation and the generalised depth discharge equation to simulate the flow of water on low slopes through a thick trash blanket a series of runon experiments were designed (Section 3.3.1)

The exponent (m) of the generalized depth discharge equation (Equation 3.6) has been the subject to many studies (Turner 1978; Turner and Chanmeesri 1984). Mahashwari (1992) postulated that, like the parameter m in the generalized form of the equation (Equation 3.6), the value of α_f in Equation 3.7 indicates the type of flow regime. Mahashwari (1992) divided the value of the exponent α_f into categories similar to m as follows:

α_f =1.0-1.67 for subdivided flow

α_f =1.67 for fully turbulent flow

α_f =1.67-3.0 for mixed flow

α_f =3.0 for fully laminar flow

The term for subdivided flow is a special case where the flow rate is independent of the flow velocity which is similar to the flow of water through porous media (Smith *et al.* 1990). This flow condition is experienced in very dense vegetation (Smith *et al.* 1990).

3.3 METHODS AND MATERIALS

3.3.1 Run on Experiments

Run on experiments were conducted to determine if the depth discharge equation (Equation 3.7) and the Manning's equation (Equation 3.5) were valid for the types of flow present within low lying sugarcane fields. The experiments were conducted over a series of weeks at the Palmas Site, which had been harvested approximately 4 weeks previously, and had a 30-50 mm thick trash blanket. The run on experiment consisted of section of;

row with low slope,

row with steep slope,

cross row at 90^{o} and,

cross row at 45^{o}.

All slope treatments were replicated with and without trash present.

A 60 m section of a representative furrow was surveyed at the lower end of the field by a laser beacon and a laser receiver attached to a survey staff. The elevation of the field was measured approximately every 20 m along three transects 10 m apart over the length of the field (Appendix Table A 1.1). From these data, 25 m sections of a single row within the field with the slopes, 0.0008 m/m (low) and 0.006 m/m (steep slope) were selected for the run on experiment (Appendix Table A1.1). The same row was used in all the row flow experiments reported below, the row was approximately 100 mm deep and 1.5 m wide at the top and 0.75 m wide at the base.

The flow velocity (V, m/s) was measured using a salt injection technique (Luk and Merz 1992). One litre of 5% NaCL solution was injected into the **baffle box** in front of the inflow flume. The electrical conductivity (EC) of the runoff water was monitored at 0.05 m, 12.5 m, and 25 m down the furrow (Figure 3.2) by EC meters. The same technique was used for the non furrow flow experiment but the EC was measured at 6 m and at 12 m.

The volume of water (q, m^3/s) passing the depth measuring points was calculated by the measurement of the water depth (y, m) the wetted perimeter of the furrow and the flow velocity (V, m/s).

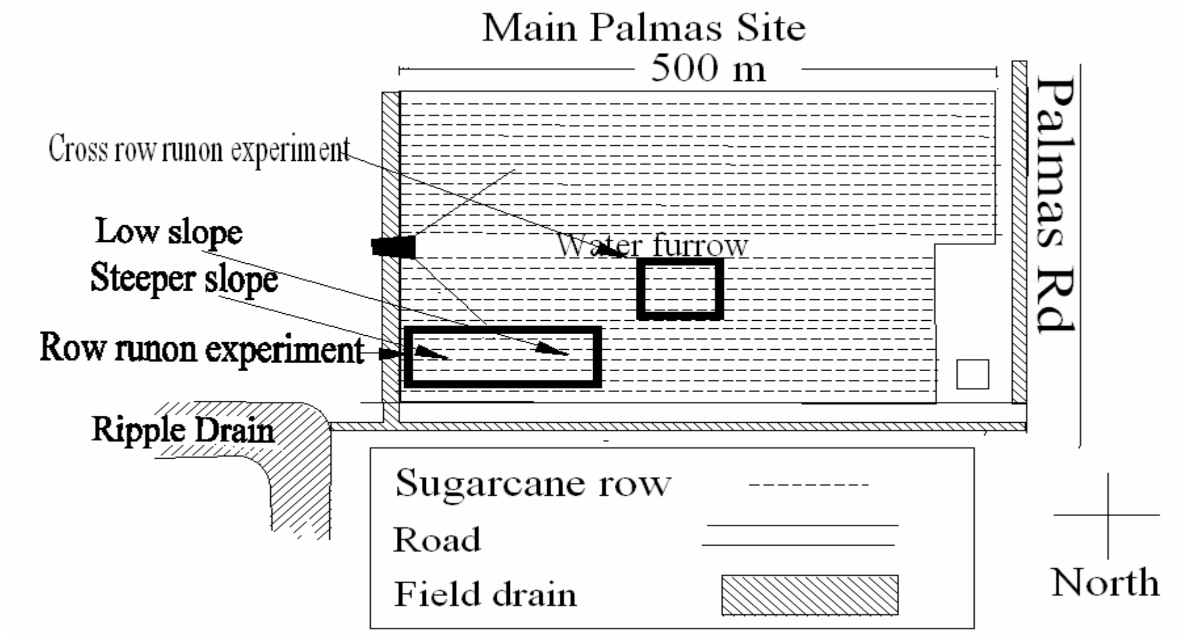


Figure 3.1 Sketch showing location of row run on experiment at main Palmas site

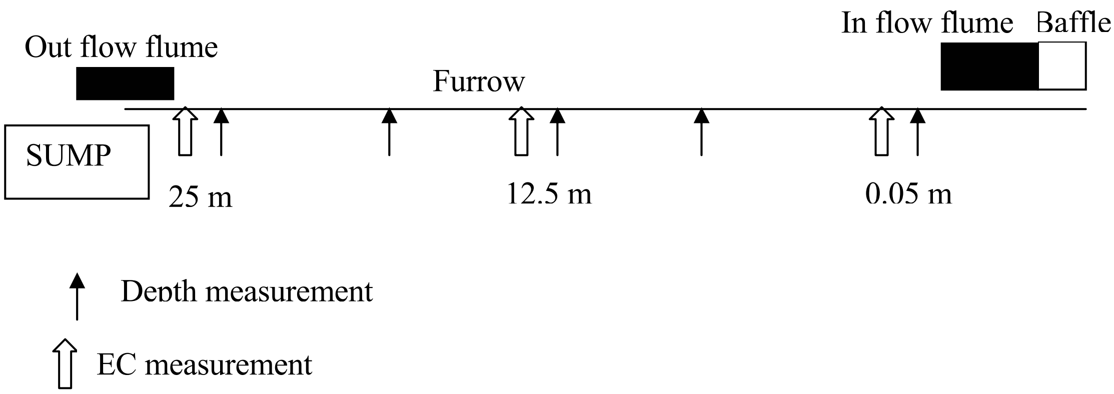


Figure 3.2 Cross section of the experimental set up of the down furrow run on experiment at the Palmas site

The treatments consisted of three replicates on the low slope (0.0008 m/m) with trash present at a low flow rate (1 L/s), and two replicates on the same slope with trash at a high flow rate (4 L/s). On the steeper slope (0.006 m/m) there were three replicates with trash present at the low flow rate, and three replicates with trash present at the high flow rates. The trash was removed and three replicates were measured at the low flow rate and two replicates with trash removed at the high flow rate. These experiments allowed the roughness coefficient n in the Manning equation (Equation 3.5), and the parameters for the depth discharge equation (Equation 3.7), to be calculated for both trash blanketed and trash free conditions.

3.3.1.1 Low slope run on experiment

The length of furrow over which the flow was measured had to be long enough to allow the flow of water to represent the typical overland flow from a rainfall event. However, the longer the section of row the more water was required. The length of row (25 m) was thought to be a suitable compromise between the need to replicate the natural process and the water availability. Initially a 3000 L tank on trailer and towed by a tractor was used as the water supply the trailer was filled from an irrigation bore located approximately 2 km away. Later water was pumped directly from Ripple Drain to supply the experiments.

The water was supplied to the baffle box to still the water, and then allowed to overflow into an eight inch **cutthroat flume** (the inflow flume of Fig. 3.2). The inflow flume was positioned in the centre of the row and elevated 0.05 m above the furrow to allow water to flow freely through the flume and not back up and submerge the flume. The water was constrained by the row walls and flowed down the interrow space. Pressure transducers with a measurement range of 0-5 m and a resolution of 2.5 mm were attached to single channel dataloggers

(Dataflow™392) were placed in the inflow and outflow flumes as well as in the row at 0.05 m, 7.5 m, 12.5 m, 17.5 m, and 25 m from the inflow flume. The dataloggers measured and recorded the depth of flow every 30 seconds (Figs 3.2, 3.3). The datalogger measured and recorded the height of the water in the stilling well of the flume every 30 seconds. The water was pumped at two rates, approximately 1 L/s and 4 L/s and flow velocities were monitored along sections of the furrow by the introduction of 1 L of a 5% NaCl solution to the inlet. Changes in the EC of the water and hence the salt plume were detected by two EC meters (TPS™ model WP84). The time taken for the peak of the salt plume to reach the 0.05 m, 12.5 m, and 25 m positions along the row were used to determine the flow velocity.

An eight inch cutthroat flume was placed at the end of the furrow to measure the out flow (outflow flume in Fig. 3.2). It was necessary to dig a hole approximately 0.5 m deep to act as a sump into which the drainage water ran (Fig. 3.2). A pump periodically emptied the water from the sump so that the water never backed up into the outflow flume. The outflow flume allowed measurement of the discharge rate as well as the time of start and finish of the **hydrograph**.

The depth of water that flowed through the inflow flume was measured by a pressure transducer with a measurement range of 0-5 m and a resolution of 2.5 mm and was recorded by an attached single channel datalogger (Dataflow™ 392).

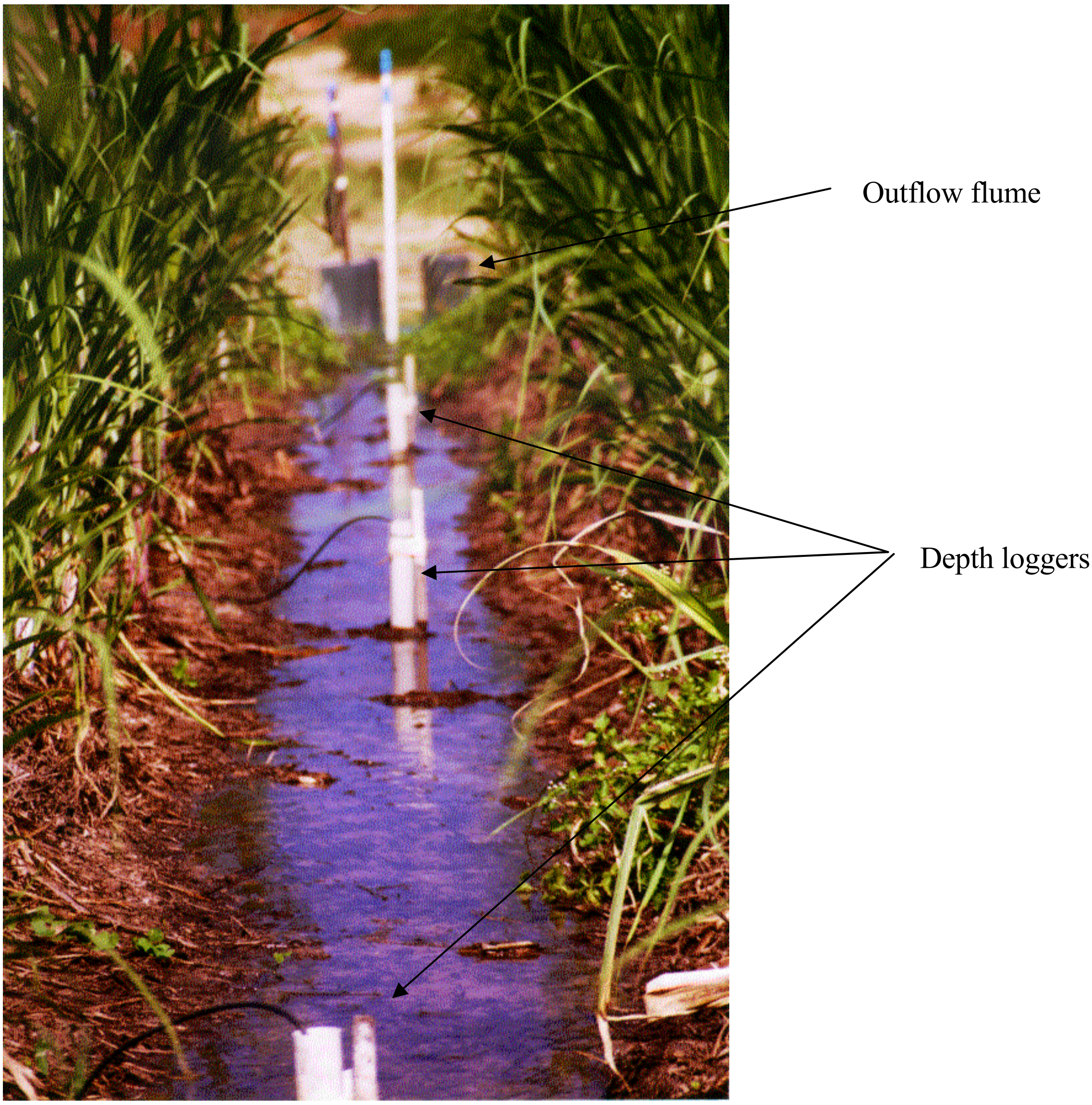


Figure 3.3 Down row component of the run on experiment showing depth loggers and outflow flume.

3.3.1.2 Steeper slope run on experiment

The second phase of the experiment was placed on a slightly steeper part of the field (0.006 m/m) (Fig 3.1), the relative location of the water height measurements being unchanged in relation to the inflow flume. The experiments were repeated on this slope with the green cane trash blanket present and with the trash removed.

3.3.1.3 Cross-row run on experiments

At the Palmas Site there was a considerable cross slope of 0.015 m/m towards the water furrow. To measure the resistance to flow across the slope an experiment was set up to simulate the non-furrow flow. Artificial channels were constructed at 90° and 45° to the furrow by using sheets of fibre cement (3.0 m long, 0.45 m high and 0.5 mm thick) that were dug into the ground 200 mm deep to form a channel approximately 2 m wide and 10 m long (Figs. 3.4 3.5 3.6). The soil was packed firmly back into the ditch to prevent leaks. The channel ran from the centre row to the row closest to the water furrow. The channel was formed at two angles, 90° to the furrow and 45° to the furrow (Figs. 3.4 3.5 3.6).Three replicates of the high flow rates were used for this part of the experiment all with trash.

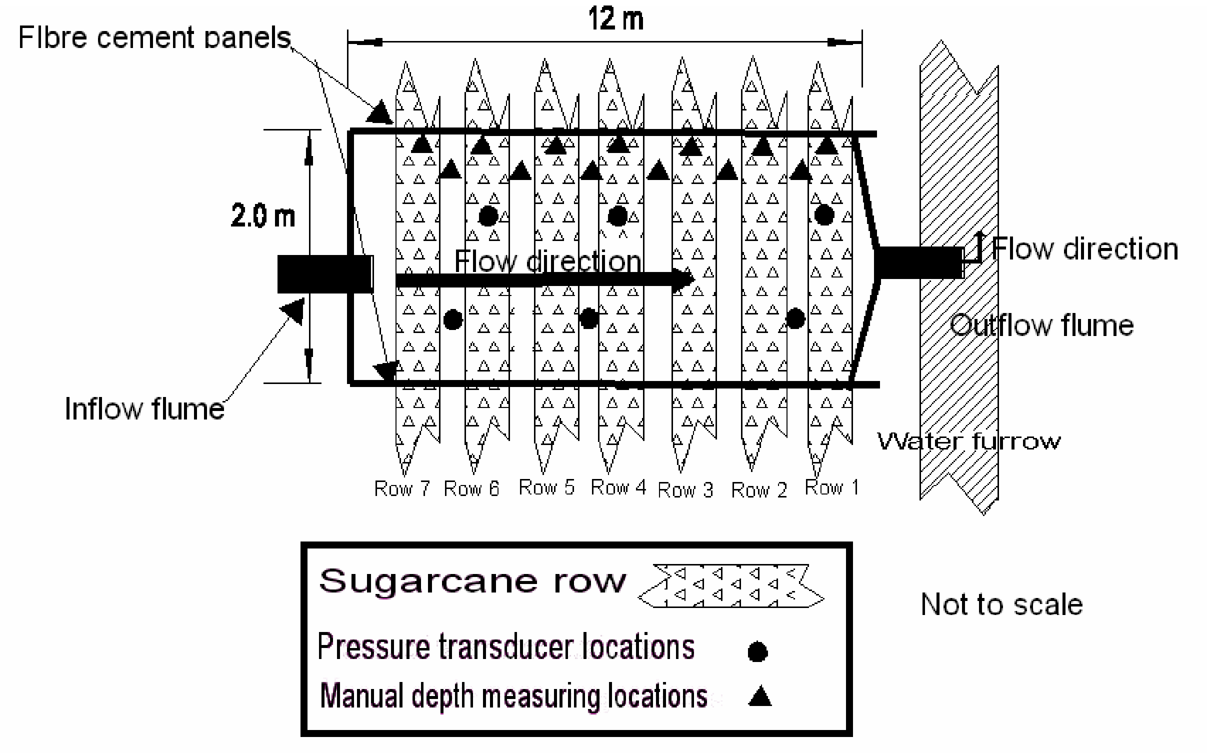


Figure 3.4 Plan of the site of the 90° cross row flow experiment

Inflow flumes and outflow flumes were installed at each end of the fibre cement channel. The outflow flume emptied the water into the water furrow. The same pressure transducers as were used in the former run on experiment were installed on top of row 1, 4, and 6 and in the interrow space between rows 1 and 2, rows 4 and 5, and rows 6 and 7. Row 1 was the nearest row to the water furrow (Figs. 3.4, 3.5).

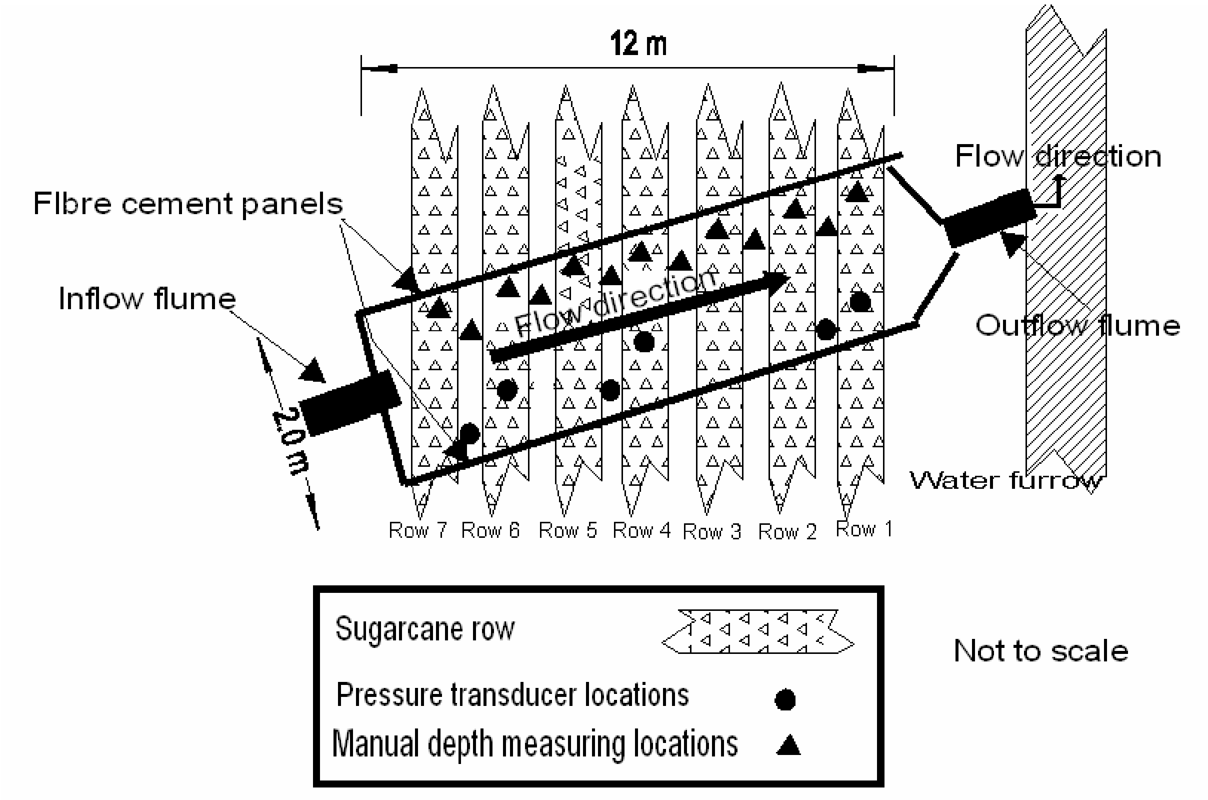


Figure 3.5 Plan of the site of the 45° cross row flow experiment

Water was pumped from the Ripple Drain into the baffle box and then flowed into the inflow flume that was raised approximately 300 mm above the level of the row to prevent submergence. The water depth was measured and recorded every 30 seconds in both flumes by pressure transducers attached to single channel dataloggers. The water depth was also measured manually at each row and interrow space during the experiment as well as being measured by pressure transducers and recorded by dataloggers every 30 seconds. Flow velocities were measured by the EC method at 0.05 m, 6.0 m, and 12.0 m from the inflow flume for each run.

Figure 3.6 Cross furrow (45^{o}) flow experiment showing fibre panels and outflow flume (left) and inflow flume (right).

3.3.2 Measurement of rainfall and runoff from low lying sugarcane fields

Rainfall was measured at the Palmas Site by a Campbell Scientific tipping rain gauge linked to a Campbell CR 10x data logger. The logger automatically down loaded daily to a computer at the CSIRO Davies Laboratory Townsville using the GSM mobile phone network.

Runoff from sugarcane fields produced by high rainfall during the wet season was measured by installation of flumes at the Palmas Site. The measured runoff was then partitioned into the volume of water draining from the row and the water furrow.

3.3.2.1 Selection of the type of flow structure

Runoff can be measured by orifices (pipes), **weirs**, or flumes of known dimensions and flow regime (Bos 1978). To measure flow accurately, pipes require fully submerged conditions and while these conditions can be manufactured, measuring the height of water within the furrow was considered more advantageous to the present study. Weirs require careful calibration, create an upstream disturbance to the flow and disrupt the natural flow of the channel; but they are extremely good for measurement of low flows (Bos 1978). Flumes also disrupt the natural flow but do not create flow disturbances like weirs. Constricted walls, or a raised floor, or both, will cause the flow in the flume to accelerate which in turn causes the flowlines to converge and create critical flow (Bos 1978). Once critical flow is achieved there is a unique relationship between the depth and the velocity of water that can be used to determine discharge (Bos 1978).

Flumes were selected as the preferred measurement structure as they present the least disturbance of the natural flow from the field. A large cutthroat field flume with a throat width of 600 mm with no exit section, was already in place at the end of the water furrow at the Palmas Site to measure the total runoff from the field (Fig 2.1 and Fig 3.7). The flume design was constrained to measure the flow from individual rows, and the flow of water within the water furrow. An ultrasonic doppler discharge meter was installed in the main field flume, with a compound rectangular V-notch weir installed at the outlet of the flume to capture the low flows (Figs 3.7-8).

To capture the water from the rows on either side of the flume, fibre cement panels (4 panels on each side of the flume) 450 mm high or 3.0 m long were dug in to depth of 150 mm at a 45^{o} angle from the entry section of the flume. The fibre panels were dug across the seven rows either side of the flume to capture the runoff from these rows.

Figure 3.7 Large field flume (Palmas Site) looking upstream showing compound rectangular V notch weir.

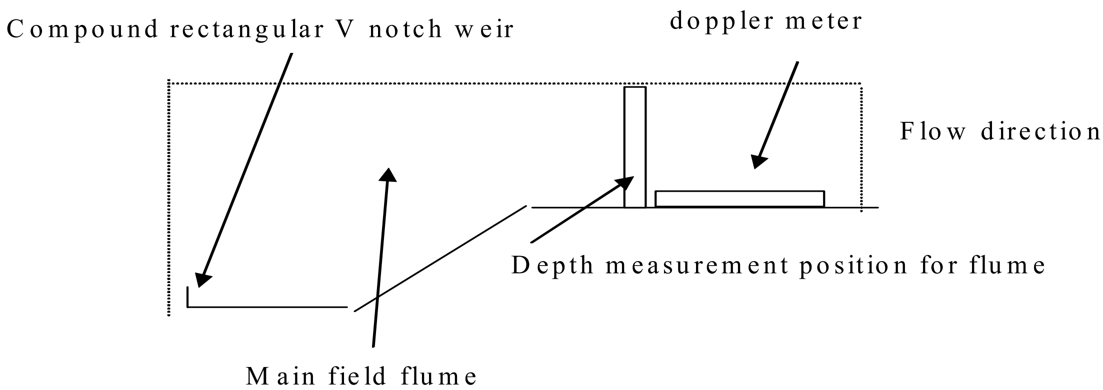


Figure 3.8 Sketch of cross section of the field flume, Main Palmas Site

3.3.2.2 Flume type

There is a large range of flume designs available. It was decided that the simplest to construct, install and modify if required, would be used. This restricted the choice to either long or **short throated flumes**. **Long-throated flumes** cause the flow lines to become parallel, and parallel fluid flow concepts can be employed to measure the discharge (Bos 1978). Short-throated flumes have either no throat or a short throat that does not produce parallel flow. Instead the flow regime is curvilinear. There is no theoretical base for discharge calculations and an empirical relationship has to be generated to estimate the discharge from a short-throated flume relative to the stage depth and velocity relationship (Bos 1978).

The advantages of short-throated flumes are the ease of manufacture and placement in the field. Cutthroat flumes are short throated flumes which have no throat, a level bottom, the same geometry independent of size, and are easy to manufacture (Skoerboe *et al.* 1972). It is possible to interpolate the discharge relationship between geometrically similar cutthroat flumes of different lengths (Skoerboe *et al.* 1972). If a cutthroat flume is manufactured and the discharge relationship is not determined but interpolated, the changed approach conditions of the flume can cause scale effects which may invalidate the interpolated flume calibration (Ackers 1978). It is recommended that if the cutthroat flume is to be used, then the design should correspond exactly with a flume already calibrated, otherwise a calibration must be carried out (Ackers 1978).

3.3.2.3 Cutthroat flume design

All the cutthroat flumes in the present study used a design from Skoerboe *et al.* (1972) (Fig. A3.1). The flumes were 914 mm (3.0 ft) long and this length was selected as it gave portability to the structure as well as allowing a range of flows to be measured.

To select the optimal size for a flume to measure runoff from an interrow, the peak flow rate of the runoff must be known or estimated. Data collected from the large field flume that drained the water furrow and the seven rows on either side of the water furrow from the four largest rainfall events from the 1997-98 wet season were selected and the peak flow rate from each event was measured. From these data, the peak flow rate per row was calculated by assuming that a uniform flow occurred over the width of the drained area. This assumption is very broad due to the high possibility of preferential flow in the water furrow. This however gave an indicative figure for the peak flow rate to be expected from the rows.

The frequency of the flow rate from the runoff events was calculated to determine the spread of flows, and a probability of 90% return was used to identify the peak flow rate (Fig. 3.9).

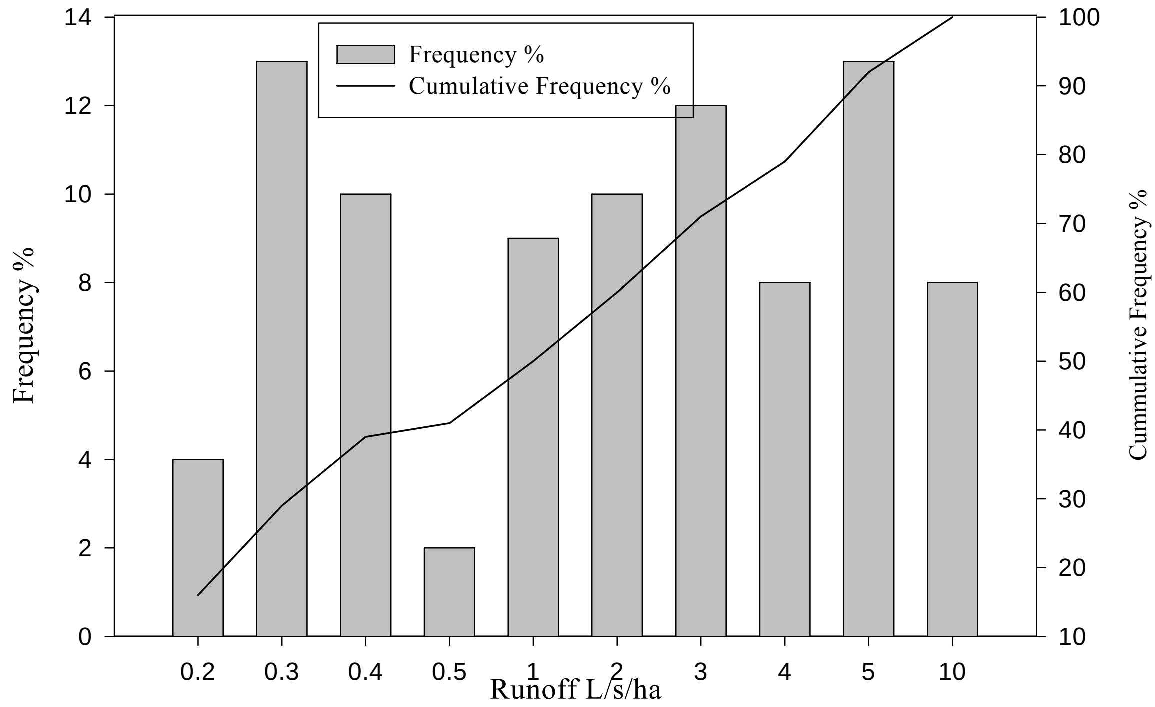


Figure 3.9 Frequency distribution of flow rates from the large field flume at the Palmas Site used to derive design criteria for in-row flumes

The 90% frequency indicated that the peak flow rate was 5 L/s (Fig. 3.9). This figure was then taken to correspond to the height and width of the rows. The rows are 0.1 m deep so a flume that would measure about 5 L/s with a water depth of 100 mm was selected. Because the flumes should be designed to cope with extreme events that can occur this was doubled to 10 L/s at 100 mm depth and cut throat flume design with an eight inch (203 mm) wide throat was selected (Skoerboe *et al.* 1972). The design for the flumes placed in the water furrow was selected by doubling the expected flow rate to 20 L/s at 100 mm using a flume with a throat width of 16 inches (408 mm).

3.3.2.4 Modification of row flume design for the 1999-2000 wet season

The eight inch cut throat flumes were found to be too wide to measure any flow from the rows in the 1998-99 wet season (Section 3.4). The flumes were redesigned using the Manning's equation (Equation 3.5) with the parameters generated from the run on experiment to predict the range of possible discharges in the following wet season.

The discharge from the model was used to redesign the small field flumes such that the throat width was reduced to 52.4 mm (2 inches) that could measure a peak flow of 2.6 L/s at a flow depth of 100 mm in the flume (Table 3.1).

Table 3.1 Predicted row discharges from a trash blanketed sugarcane field with a slope of 0.008 m/m.

Depth of water (mm)	Predicted discharge from Manning's (L/s)
10.00	0.05
20.00	0.16
30.00	0.31
40.00	0.50
50.00	0.73
100.00	2.31

3.3.2.5 Flume calibration

The calibration equation for cutthroat flumes from Skoerboe *et al.* (1972) is:

$$Q = C_f h_a^{n_1} \qquad \text{Equation 3.8}$$

Where
Q is the discharge (cu ft/sec)
C_f is the free flow coefficient
h_a is the upstream depth (ft)
n_1 free flow exponent

Equation 3.8 uses values for the coefficient and exponent (Table 3.2), requires the parameter upstream depth (h_a) in feet, and calculates the discharge (Q) in cu ft/sec. The upstream depth, measured in millimetres and converted to feet by multiplying the upstream depth (h_a) by 0.00328, was substituted into equation 3.8 and the discharge was calculated. The calculated discharge (Q), in cubic feet per second was then converted to litres per second by multiplying by 28.2. To calculate the discharge from the large field flume the depth (h_a) equation 3.8 should be in mm.

Table 3.2 Free flow coefficients and exponents for cutthroat flumes (from Skoerboe *et al.* 1972)

Throat width (W)	600 mm	402 mm (16 inches)	204 mm (8 inches)	50.2 mm (2 inches)
Flume length (L)	1.2 m (4.0 feet)	914 mm (3.0 feet)	914 mm (3.0 feet)	914 mm (3.0 feet)
C_f	0.0784	6.04	2.97	0.719
N_1	1.782	1.84	1.84	1.84

3.3.2.6 Recession coefficient

After the runoff was measured, the discharge hydrograph was plotted and the peak depth of discharge, the time of peak runoff, the total volume of runoff, and the recession coefficient (τ) were determined following the approach of Post and Jakeman (1996).

The peak depth of discharge and total volume of runoff were calculated from the measured data and the **recession coefficient** (τ) was defined as the difference between the time of peak runoff (t_p) rate and the time at which the runoff was $\frac{t_p}{e}$ (Post and Jakeman 1996); (Fig. 3.10) where e is the natural logarithm (Equation 3.9). This parameter measures the rate of recession of water from the field (Post and Jakeman 1996). Hence the smaller the recession coefficient the quicker the water has drained from the field.

$$\tau = t_p - t_{q\frac{t_p}{e}}$$ Equation 3.9

where

τ is the recession coefficient (hrs)

t_p time of the peak flow rate from runoff initiation (hrs)

$\frac{t_p}{e}$ is the time of the peak flow rate from runoff initiation divided by the natural log e

$q\frac{t_p}{e}$ the discharge at the time of the peak flow rate from runoff initiation divided by the natural log e

$t\,q_{\frac{t_p}{e}}$ time at which the discharge is equal to the time of the peak flow rate from runoff initiation divided by the natural log e (Post and Jakeman 1996)

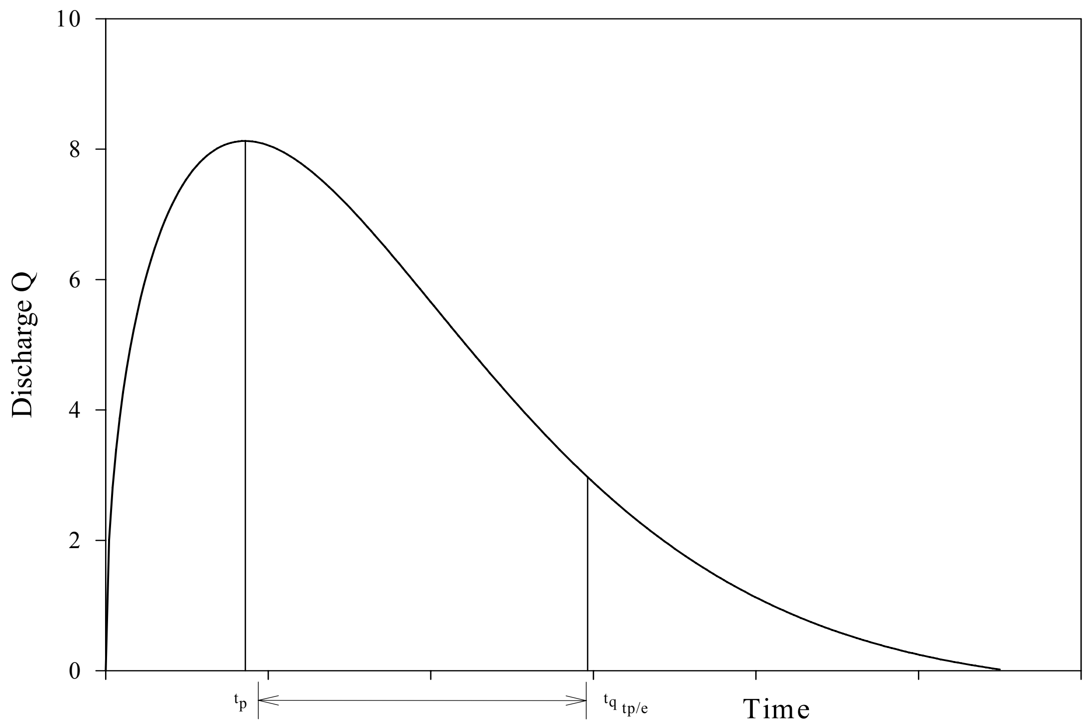


Figure 3.10 Definition of the recession coefficient (τ) from a plot of discharge with time. The parameter t_p and $t_{p/e}$

3.3.2.7 Flume location

The flumes were located to capture the different flows that occur in a field during and after rain. The slope of the Palmas Site field was surveyed by taking measurement of elevation along three transects 10 m apart, and at points 20 m apart along each transect (Fig. 3.11). There was a relatively even slope down the field so the flumes were equally spaced along the length of the field and water furrow.

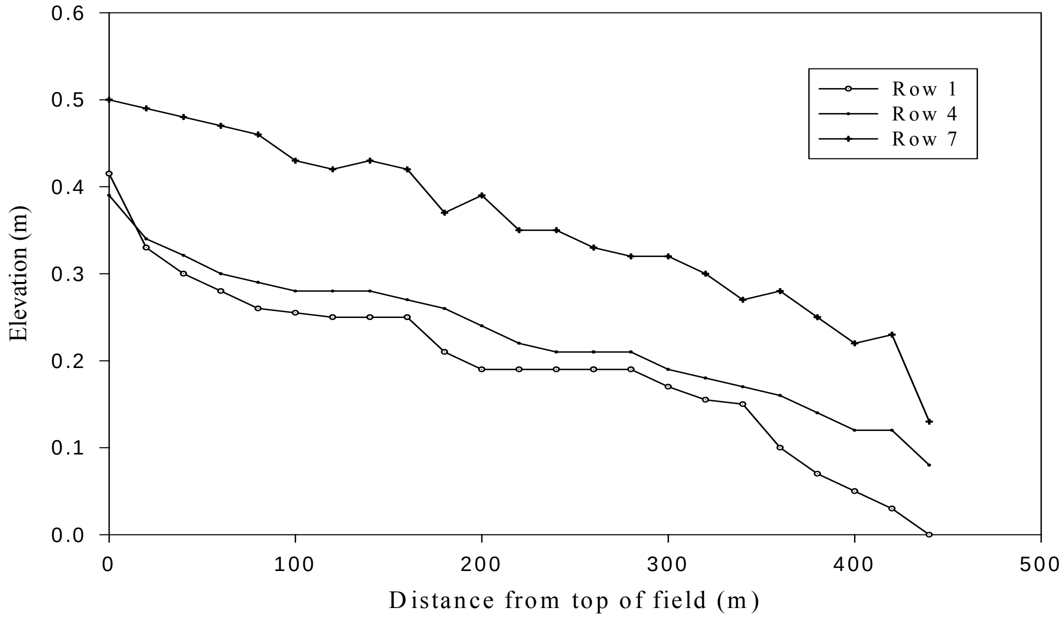


Figure 3.11 Variation in the field elevation at the Palmas Site. Height datum was the floor of the main field flume.

3.3.2.8 1998-99 flow measurements

Four eight inch cutthroat flumes were used within the rows at the Palmas Site for the first measurement period, 1998-99 wet season. Two sixteen inch cutthroat flumes were used in the water furrows and three eight inch flumes were sited at the end of the rows, and one at the top of the water furrow (Fig. 3.12). Metal strips, 100 mm high and 500 mm long, were placed diagonally across the interrow space to the outer walls of the flumes to direct water into the in row flumes. Dataflow^{tm} 392 single channel dataloggers with 5 m pressure transducers and a 2 mm water depth resolution were installed to measure the depth of water in the flumes. The loggers recorded the height of the water in the flume every 5 minutes. The dataloggers were downloaded every month using a laptop computer.

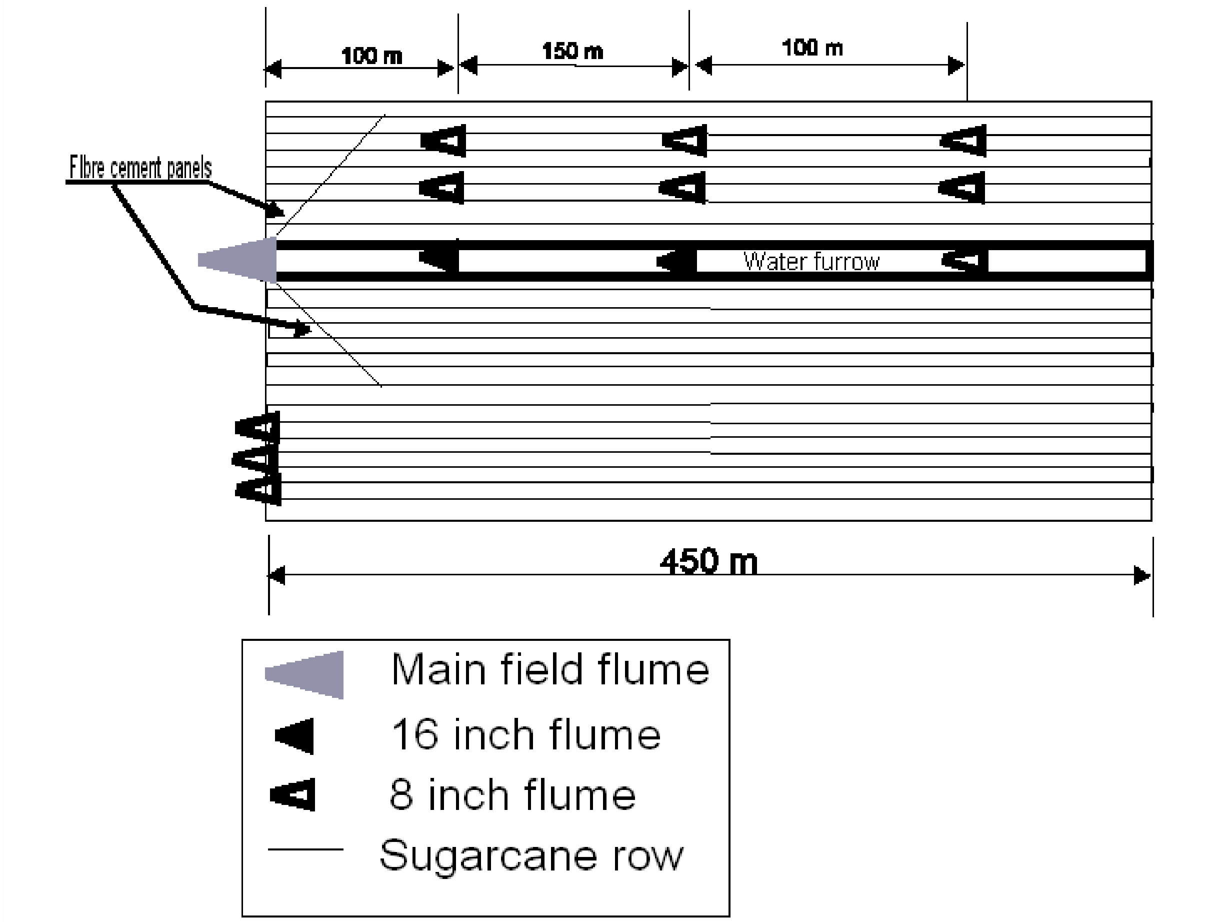


Figure 3.12 Sketch of the 1998-99 runoff field measurement instrumentation at Palmas Site

The three flumes at the end of the rows measured the amount of runoff from individual rows, flumes placed at 100 m, 250 m, and 350 m from the bottom of the field and flumes in the water furrow measured the amount of runoff that was generated within the sections of the individual rows and water furrow.

3.3.2.9 1999-2000 flow measurements

A variety of structures was used to measure the runoff from the field in the second wet season of the study (Fig. 3.13). At the Palmas Site, the original sixteen inch cutthroat flumes were modified to measure submerged flow in the water furrow by the installation of a second depth measurement location in the exit section of the flume (Fig. A3.1). A pressure transducer linked to a single channel logger was used to measure the depth at this point. Two inch cutthroat flumes (Skoreboe *et al*. 1972) were used at the ends of the rows as well as a compound 60° V-notch rectangular weir (Bos 1978). An ultrasonic doppler discharge meter was installed in the main field flume, with a compound V-notch rectangular weir installed at the outlet of the flume to capture the low flows (Figs 3.7, 3.8). Dataflow™ 392 single channel loggers with 5 m pressure transducers and 2 mm water depth resolution were installed into the structures and the loggers recorded the height of the water every 5 minutes.

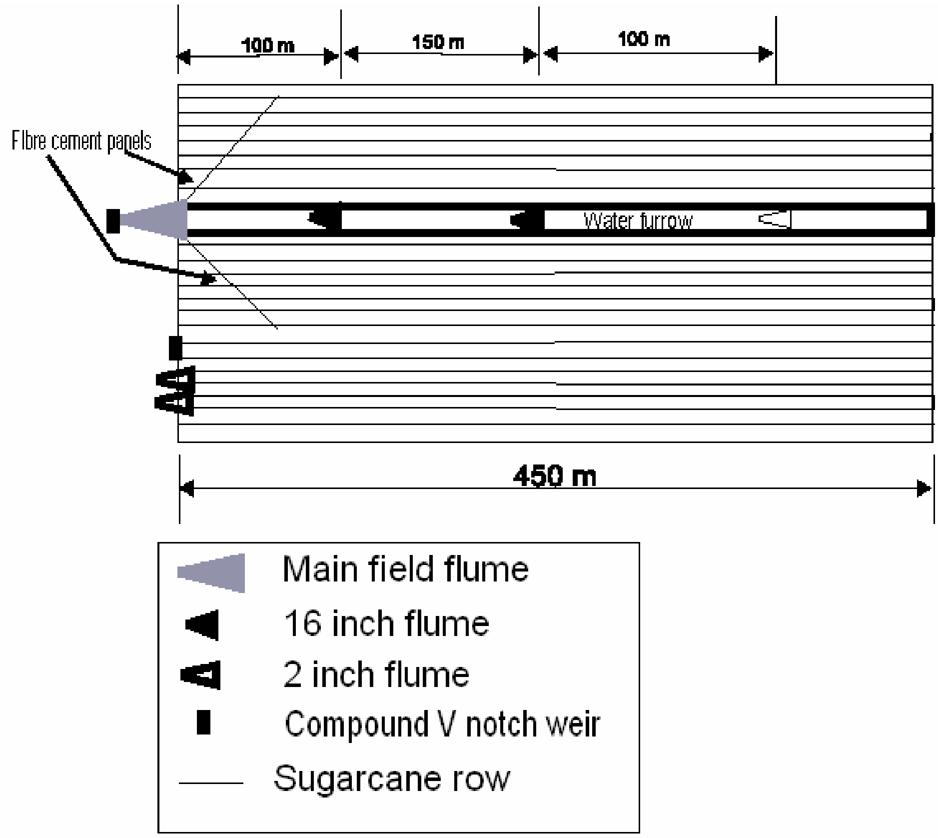


Figure 3.13 Sketch of the 1999-2000 runoff field measurement instrumentation at Main Palmas Site

At the Lasered Palmas Site (Fig. 3.14), two 2-inch cutthroat flumes and a compound V-notch rectangular weir were installed at the end of the rows in December 1999. Metal strips 120 mm high and 500 mm long were placed across the rows at the entrance of the flumes to direct the runoff into the structures.

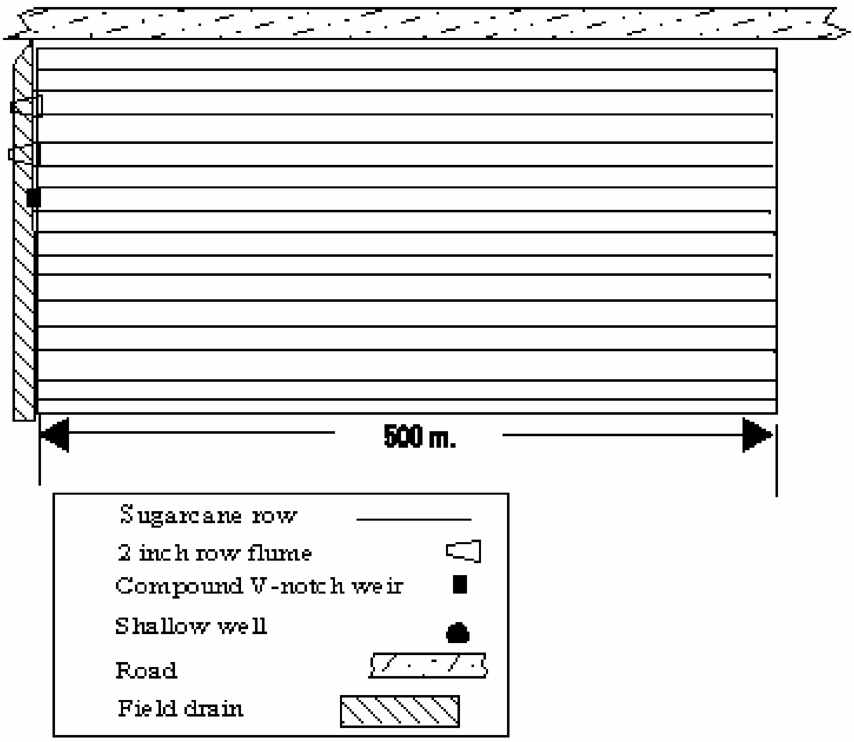


Figure 3.14 Lasered Palmas Site instrumentation 1999-2000

At the Macknade Mill site two **San Dimas flumes** (Wilm *et al.* 1938) were instrumented with Dataflow™ 392 single channel loggers with 5m pressure transducers (Fig. 3.15). The flumes were located at the outlets of individual plots. Each plot was 20 m long and 17 rows wide, one plot had a slope of 1:792 and the other plot was laser levelled flat (J Reghenzani pers comm)

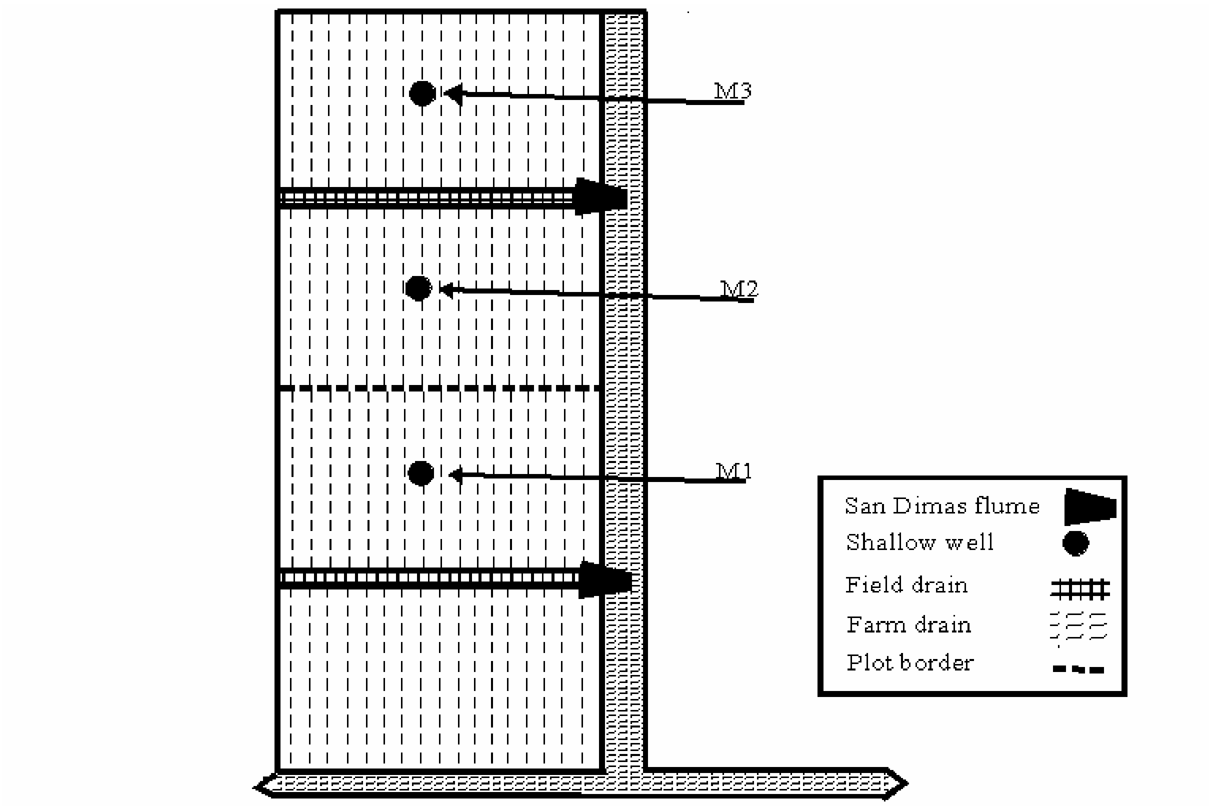


Figure 3.15 Macknade site instrumentation 1999-2000 where M1 M2 and M3 are the locations of the shallow wells

3.4 RESULTS

3.4.1 Run on experiments

3.4.1.1 Resistance to flow and flow velocity

Water was delivered to the furrow from a flume, raised 50 mm above the height of the inter row at two nominal flow rates, high and low. Water flowed down the furrow and was impeded by the thick trash blanket with fingering and division of the flow evident at the water **advance front**. The water was at most times under a trash blanket, and the high water application rates were used in an attempt to bring the flow above the trash blanket, but such flow rates could not be achieved because of the thick nature of the trash and the small size of the available pump.

Flow across the rows was difficult to simulate due the high resistance created by the shape of rows. Initially when the water ran out of the flume and into the artificial fibre cement channel, the water pooled on the high side in the interrow space and then spilled over the sugarcane row into the lower interrow space. When the interrow spaces were all full, the water flowed freely through the outflow flume and into the water furrow. The flow of water was impeded by the rows and the stems of the cane. Even at high inflow rates (5-7 L/s) the final flow velocity was similar to the flow velocity of the furrow simulation with trash (Table 3.3).

Table 3.3 shows the average of the flow velocities recorded in the run on experiment and how the varied treatments affected the flow velocity. The treatments were; flow direction of the water in the run on experiment, (either down the row, at 90^{o}, or at 45^{o} to the row); the flow rate of the water (either high or low); and the presence or absence of trash. The slope of the furrow was also noted. The measured depth of the water flow combined with the flow velocities for each treatment was used to calculate the discharge at each measurement point along the row (Appendix Table A1.2).

The presence of trash had a major effect on the flow velocity, discharge volume and resistance to flow. The flow velocity was reduced by half when trash was present compared to when trash was absent from the row (Table 3.3). The average low flow velocity with trash was 0.023 m/s when the trash was removed the average velocity was 0.065 m/s. Similarly with the high flow rates, the trash treatment reduced the average flow velocity from 0.142 m/s to 0.066 m/s (Table 3.3).

Detailed cross sectional measurements of the furrow shape (Appendix Table A1.2) coupled with velocity and depth of the flow (Appendix Table A1.3), enabled determination of the flow rate along the furrow. A significant volume of water appeared to infiltrate into the permeable well structured soil of the row that formed the furrow walls and appeared on top of the poorly structured soil of the interrow space. This water was not measured and confounded the determination of **residual or surface storage**, as this estimate relied on the difference between the volume of water delivered and the volume of water drained.

Table 3.3 Average flow velocity and slope of furrow from run on experiments

Slope m/m	Flow Direction	Flow rate	Average measured inflow rate L/s	Surface condition	Average flow velocity m/s	Standard Deviation
0.0008	Row	Low	Not measured	Trash	0.029	0.009
0.006	Row	Low	0.4	Trash	0.026	0.006
0.006	Row	High	1.6	Trash	0.071	0.016
0.006	Row	Low	0.5	No trash	0.075	0.002
0.006	Row	High	1.1	No trash	0.156	0.00
0.03	90^{o}	High	2.3	Trash	0.026	0.002
0.03	45^{o}	High	6.3	Trash	0.030	0.006

3.4.1.2 Fitting a depth discharge relationship

The depth and width of the flow, combined with the flow velocity were fitted to a depth-discharge equation (Equation 3.7) and the Manning's equation (Equation 3.5). The measured slope and water depth were substituted into the Manning's equation using a nominal value of 0.3 for the Manning's n and for the parameters ς or α_f and the equation solved. The measured discharge was compared to the discharge predicted by either the Mannings or the depth discharge equation by calculation of the residual mean square error (RMSE) between the predicted and the measured discharge. The sum of the RSME was minimized using the Solver algorithm in MS Excel by incremental change of the Manning's n. In the case of the depth discharge equation, either ς or α_f was determined by the same method then fixed, and then the other parameter was determined. As there were two unknowns this optimisation may have caused the value for the determined parameter to be a local minima so when both parameters where determined, the values were recorded and then the procedure was reversed with the parameter derived last being determined first. When both sets of equation parameters were estimated the depth discharge equations were calculated and the best fit as determined by the coefficient of determination (r^2) (Steel and Torrie 1986) was determined.

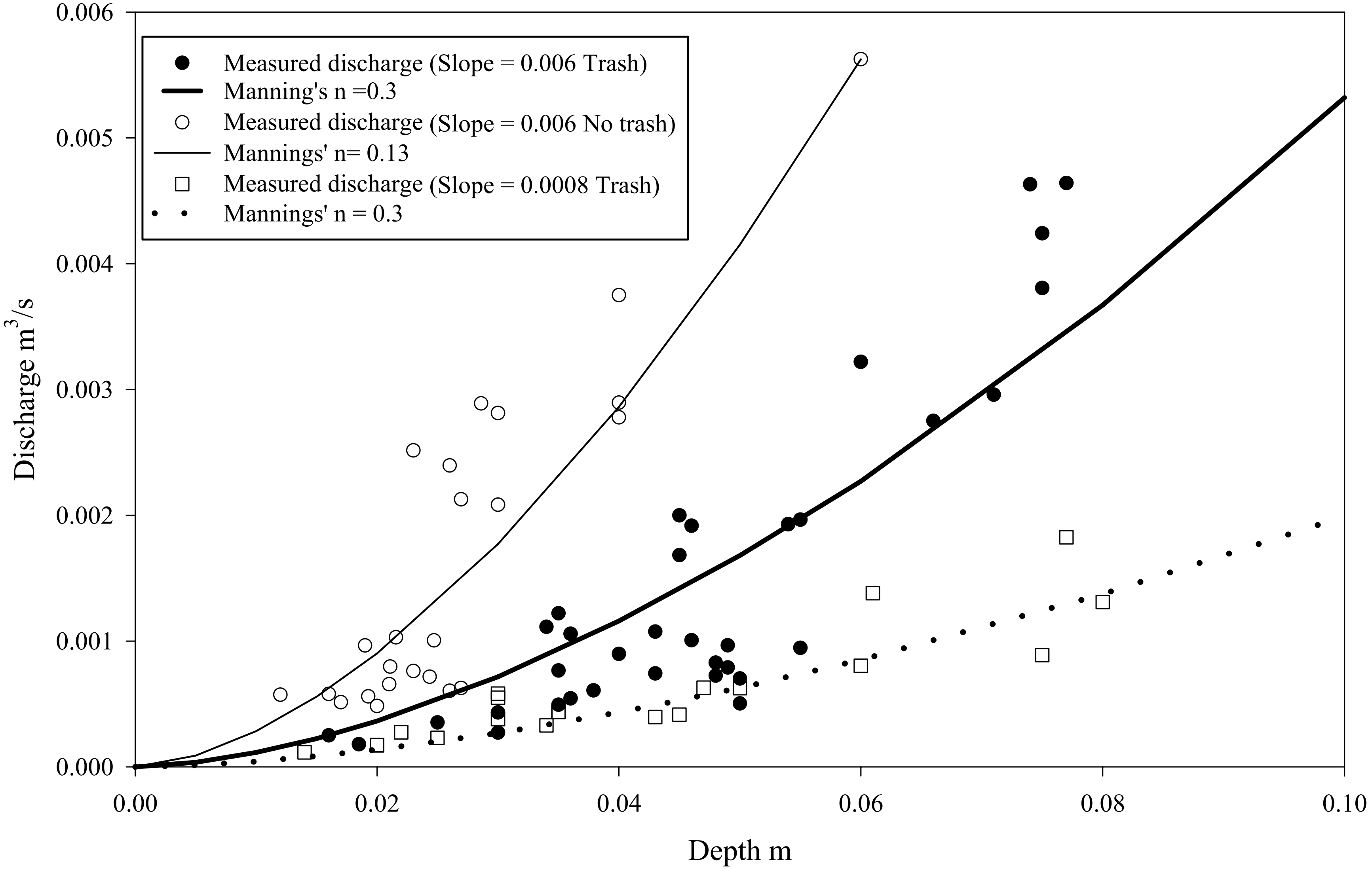


Figure 3.16 Fitting Equation 3.5 to obtain Manning's n to data from run on experiments with different slope and surface conditions (Table 3.4)

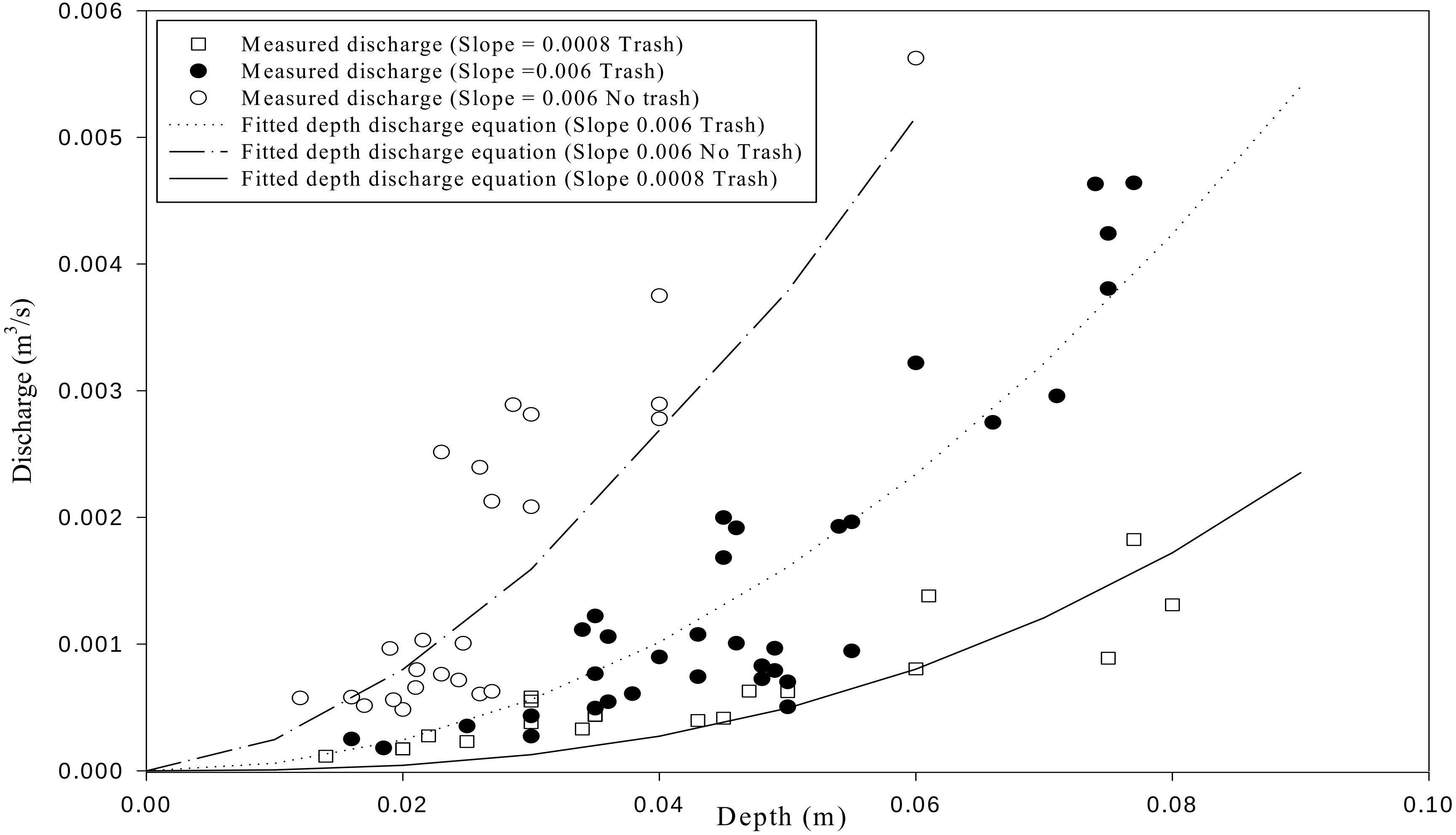


Figure 3.17 Fitting Equation 3.7 to obtain α_f and ς for the depth discharge equation from data from run on experiments with different slope and surface conditions (Table 3.4)

The Manning's equation fitted the measured data extremely well with very high coefficients of determinations (r^2) (Fig 3.16; Table 3.4). The high (r^2) value determined in the row flow with trash is possibly due to the mixing of the flow and the lower flow velocities as compared to the no trash treatment (Table 3.3). The no trash data had the most scatter in the data (Fig 3.16) possibly due to the higher flow velocities, and is indicated by the slightly lower (r^2) (Table 3.4). Overall the data sets showed that the measured data fitted the Manning's equation well.

Table 3.4 Fitted Mannings n and depth discharge parameters from data collected in the run on experiment

Field conditions		Manning's n (Fig. 3.17)	Coefficient of determination (r^2)	Depth discharge parameters (Fig. 3.18)		Coefficient of determination (r^2)
Surface condition	Slope			α_f	ς	
With trash along row	0.0008	0.31	0.99	2.66	50.00	0.99
With trash along row	0.006	0.31	0.99	2.06	10.00	0.83
Without trash along row	0.006	0.13	0.97	1.69	7.90	0.77
90^o to furrow	0.007	1.05	0.99	3.00	0.0000043	0.97
45^o to furrow	0.0065	2.62	0.99	3.00	0.0061	0.94

The measured data (Fig. 3.17) also fitted the depth discharge equation well but not as well as the Manning's equations did as measured by the coefficient of determination (r^2) (Table 3.4).

the coefficient of determination measures the amount of variance the fitted parameters explain (Steel and Torrie 1986). The high r^2 of the regression mean that the fitted Mannings n value explain up to 99% of the variation.

The Manning's equation uses one less parameter than the depth discharge equation and this more parsimonious use of parameters by the Manning's equation made it a more robust choice (Table 3.4) than the depth discharge equation.

3.4.2 Runoff measurement

3.4.2.1 Runoff from Palmas Site

Rainfall for the study period has been described above (Table 1.2). Runoff from the Palmas Site in the 1998-99 wet season was characterized by flow depths of up to 200-300 mm. One deep runoff event of 650 mm occurred during the March flood (Fig. 3.19). This was in contrast to the 1999-2000 wet season when five deep runoff events of 500-600 mm occurred (Fig. 3.20). A series of smaller runoff events of depths of 100-160 mm occurred in February 2000 (Fig. 3.20).

- *Runoff depth*

The 1998-99 wet season was characterized by persistent rain and, during the period between early December 1998 and June 1999, twelve separate runoff events were recorded in the main field flume (Fig 3.18). On 12 February 1999, 159 mm of rain fell which resulted in regional flooding; runoff from outside the field entered and flowed through the flume. This is indicated as the peak height of runoff measured in the flume was 650 mm which is approximately 150 mm higher than the elevation of the top of the field above the flume (Fig. 3.18). The other runoff events were smaller and the peak runoff heights were 250-300 mm (Fig. 3.18)

Measurement of the runoff from the 1999-2000 wet season commenced in 2 December 1999 but equipment failure (rat damage and battery failure) resulted in no data recorded until 31 January 2000. Nevertheless the 1999-2000 wet season had a different rainfall pattern with 4 rainfall events causing regional flooding on 6, 24, 29 February and 10 March 2000 (Fig. 3.19).

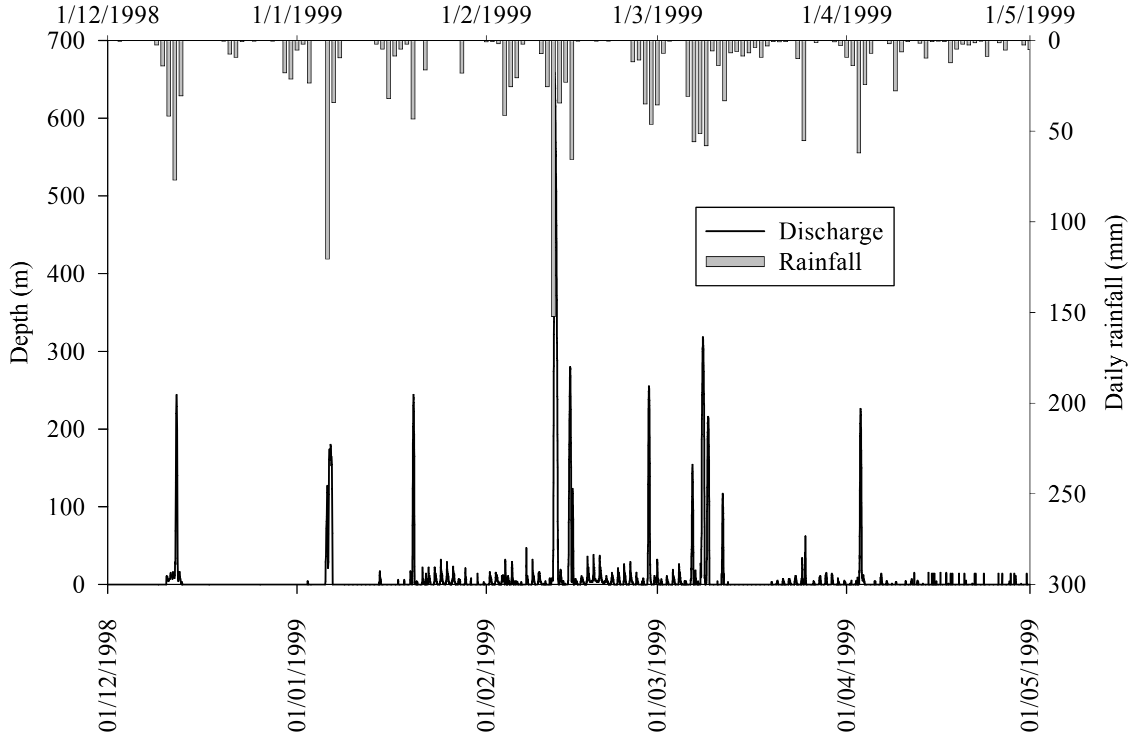


Figure 3.18 Daily rainfall and runoff depth recorded in main field flume 1998-99

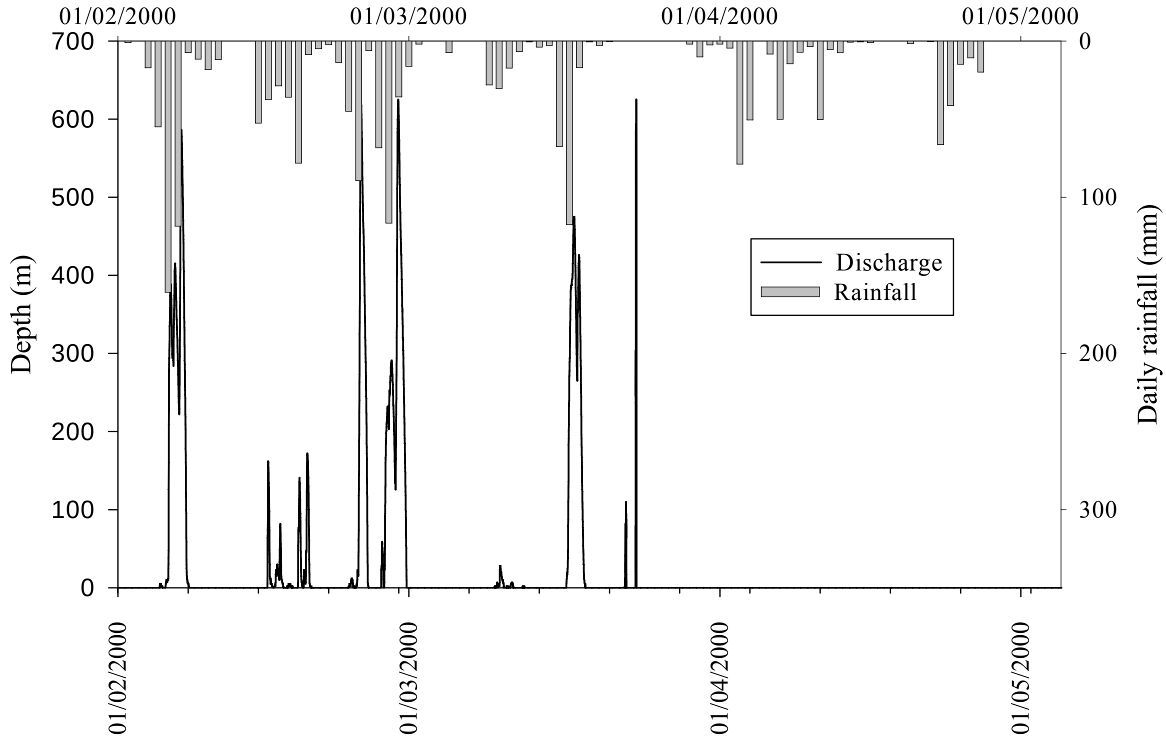


Figure 3.19 Daily rainfall and runoff depth recorded in main field flume 1999-2000. No records collected in the period from 2 December 1999 and 31 January 2000 due to rat damage and battery failure

However there was a series of smaller events between 15 and 19 February 2000 when the field was not overtopped and it was possible to use these events to measure field runoff (Fig. 3.19).

- *Runoff volume*

Runoff rates determined from the Palmas Site flume in the 1998-99 season were calculated by conversion of the depth of runoff measured in the flume to a discharge by the flume calibration equation (Equation 3.8). A simple mass balance calculation was performed on the data collected from the runoff event on 12 December 1998. The flow rate calculated by the flume calibration showed that 240 L/s was supposedly discharged at peak depth through the flume (Fig 3.20). The total volume of runoff, calculated by the flume calibration was 447 mm compared to the rainfall of 75.5 mm. This observation suggested that the runoff regime may be more complicated than first thought. It was originally thought that the drainage water ran freely from the fields into

Ripple drain. However the data collected from this event suggested that this was not correct. As additional runoff events were measured they were examined to determine what the processes occurred that controlled runoff.

In the rainfall event on 10 January 1999 that caused extensive regional flooding, water in the flume was 650 mm deep which corresponded to a discharge of 1400 L/s (Fig. 3.20). This flood event was known to have caused the drainage system to overfill, and for water to stand in the flume.

The next rainfall event which occurred on 19 January 1999 is examined in detail in the following section.

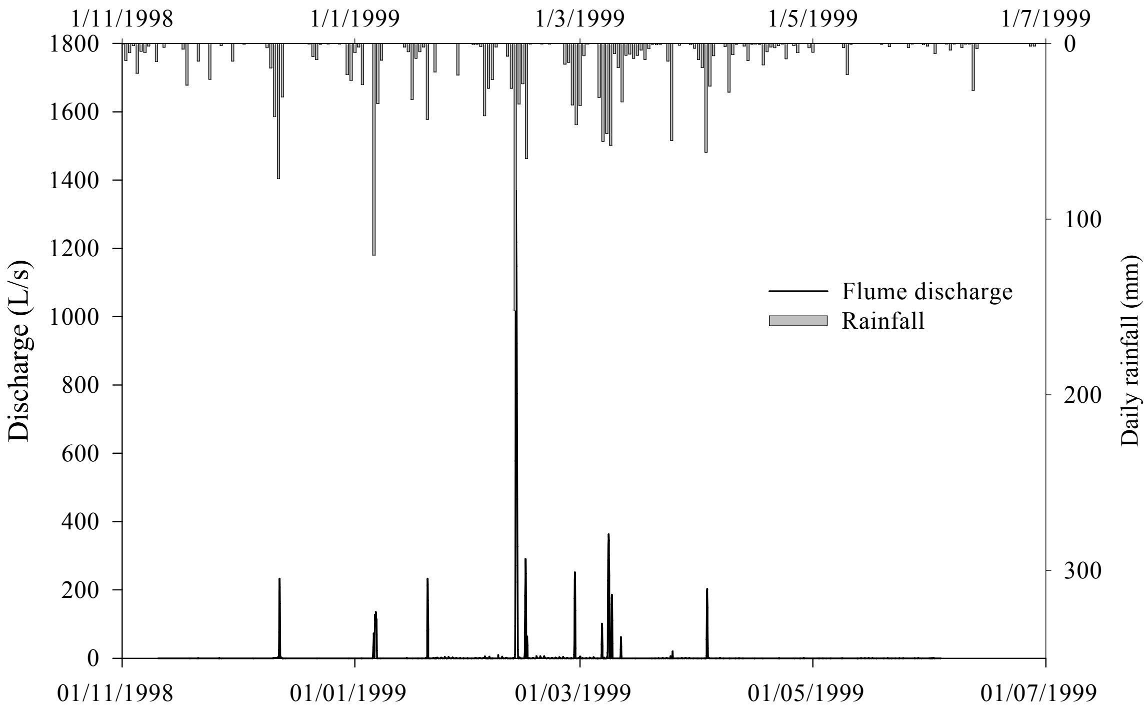


Figure 3.20 Rainfall and discharge from the Palmas Site flume during the 1998-1999 wet season, assuming free flow of water through flume.

- *Evidence of backwatering*

The water depth in the Ripple Drain was measured hourly by a pressure transducer linked to a single channel logger (H. Bohl, pers. com) approximately 50 m from the main field flume. The depth of water in the drain during the 19 January 1999 event was compared to the main field flume hydrograph. Both sets of data were plotted as height above the bottom of the Ripple drain (Fig. 3.21). This comparison showed that the height of the water in the drain and flume were similar which suggests that the water from the drain impeded the flow from the field. The shape of the field flume hydrograph shows a peak of flow from the field followed by a small decline at 11:30 pm on 20 January 1999 (Fig. 3.21). From this point on the field and regional drain hydrographs closely match.

It is hypothesised that initially runoff from the field was not restricted and produced the first peak at 10:30 pm 20 January (Fig 3.21), and this discharged freely into the Ripple Drain. It is then thought that the flow of water from the field then started to decrease, but the flow of this water was impeded downstream by water from the overfull drainage system. It is assumed that Ripple Drain filled with runoff from higher in the catchment and this water impeded the flow from the field which then produced the second and larger peak at midnight 20 January (Fig 3.21). This process caused water to back up and change the flow conditions in the flume from free flow to submerged flow. By 2 am on 21 January, the flow in Ripple Drain was unobstructed and the hydrograph of the field closely matched that of the drain (Fig 3.21). To measure this type of flow both the depth and velocity need to be recorded. A Unidata Starflow model 6526B-21 **ultrasonic doppler flow velocity meter** was installed in the middle of the inflow section of the large field flume adjacent to the stilling well (Section 3.2.2) late in the 1998-1999 wet season (Figs. 3.8, 3.13). This device measured the velocity and height of the runoff and, with the known cross section of the field flume it allowed discharge from the field to be calculated.

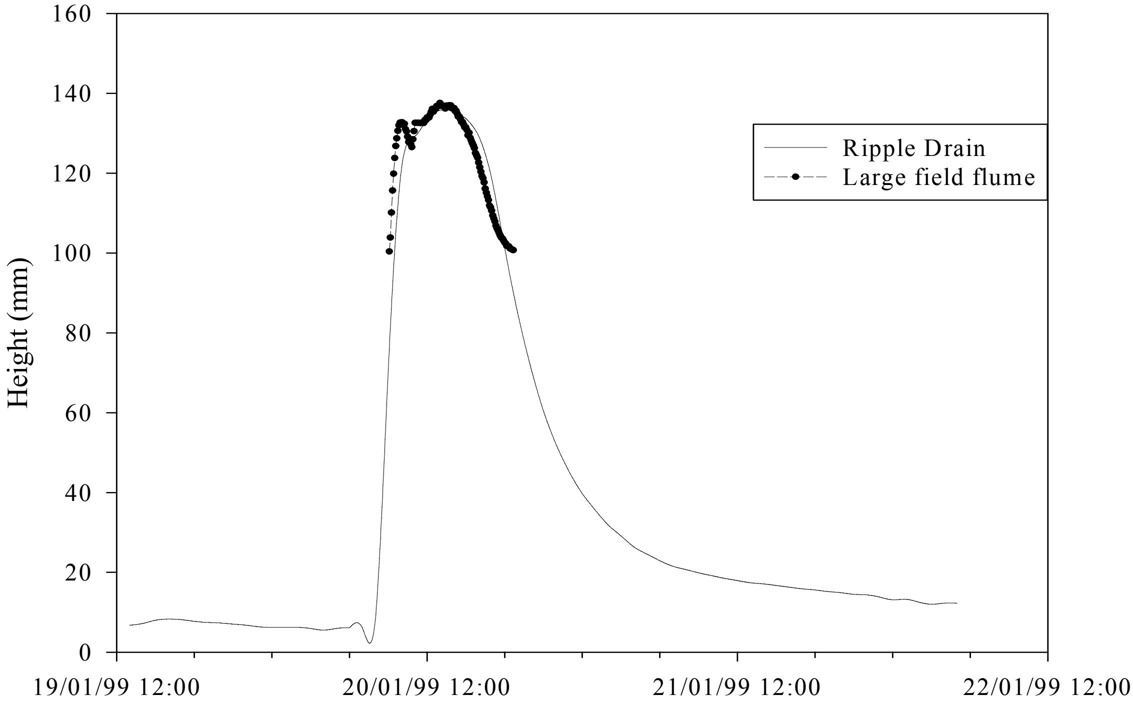


Figure 3.21 Depth of water in Ripple Drain and Palmas Site flume plotted on the same datum

This meter measured both the velocity and the depth of the water in the flume for the next major rainfall event on the 3 April 1999, when the water in Ripple Drain again backed up. Figure 3.22 shows the measured water velocity and water depth from the 3 April 1999 event. The velocity reached a peak well before the runoff depth had peaked. When the runoff was the deepest, the velocity had decreased from a maximum of 275 mm/s to 75 mm/s (Fig 3.22). The peak in velocity corresponds to the timing of the peak rainfall rate that was measured in hourly intervals from midnight. Water draining from the field cannot do so freely into the Ripple Drain if the drain is full and impedes the water discharged from the field; this process decreases the velocity of the water and the increases the depth of water in the flume (Fig. 3.22). The water can only completely drain from the field when the height of water in the Ripple Drain is lower than the elevation of the bottom of the field.

The large field flume at the Palmas Site was not designed to measure submerged flow and the application of the free flow equation is predicated on the assumption that free flow occurred in the flume. As free flow did not occur, the calculated discharge from the measured water depth and flume calibration (Equation 3.9) was meaningless.

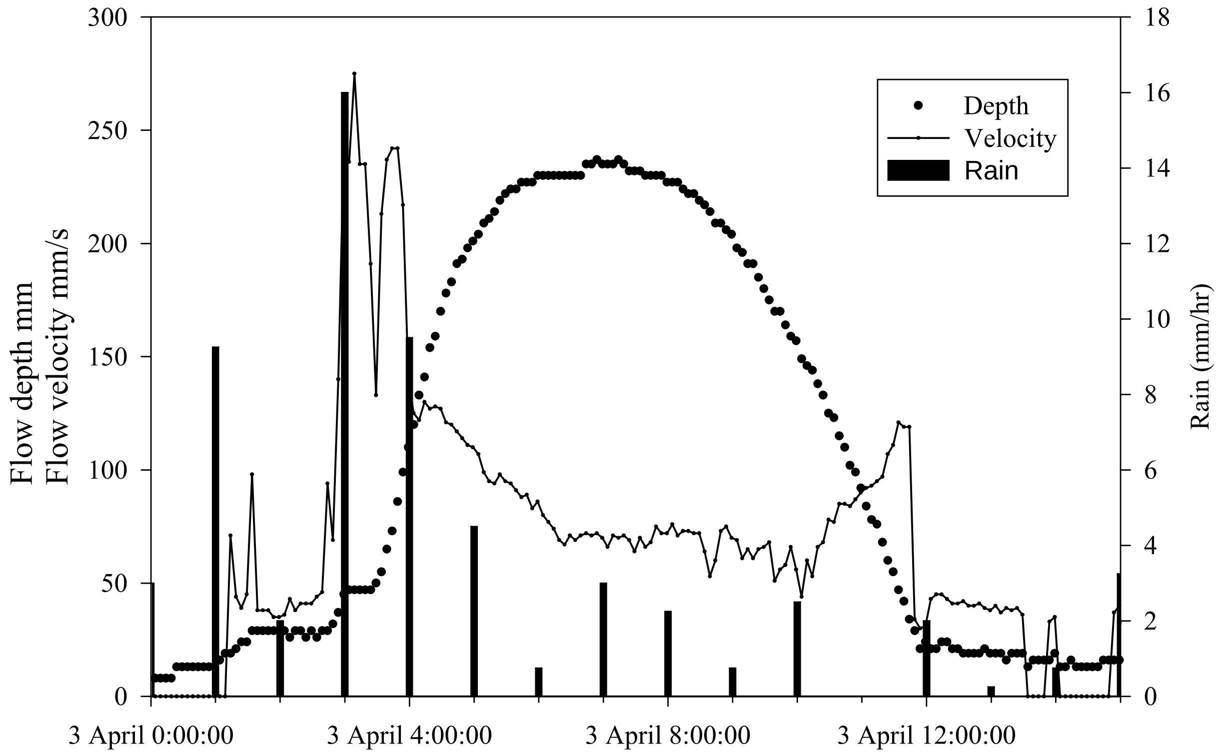


Figure 3.22 Measured velocity and depth of runoff from the field flume

To confirm the breakdown of the free flow conditions in the flume for the 3 April 1999 rainfall event when backwatering occurred, the predicted velocity calculated from discharge from the field flume calibration equation (Equation 3.8) was plotted against the measured runoff depth (Fig. 3.23). The predicted velocity increased with increasing depth however the measured velocity remained between 100-200 mm/s and independent of the depth of the water in the flume (Fig. 3.23). When the flow is the shallowest (less than 50 mm), there is reasonable agreement between the predicted and measured velocities however flows deeper than 50 mm show that the velocity was independent of the depth.

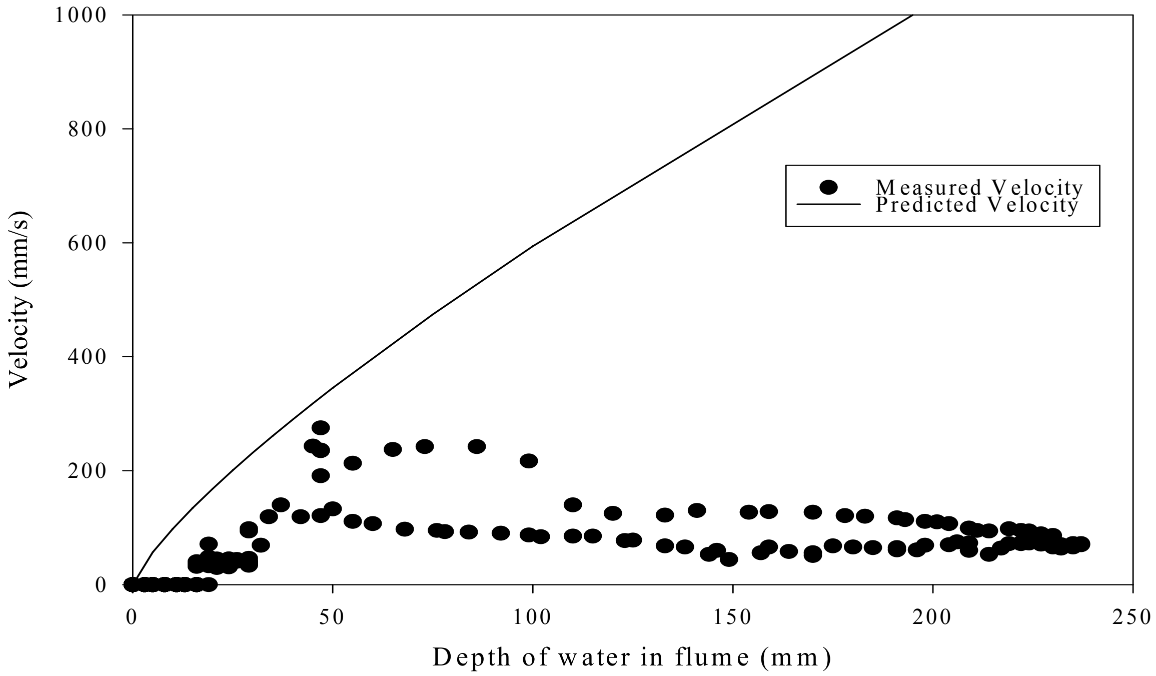


Figure 3.23 Comparison of measured velocity of runoff to predicted velocity in the large field flume at the Palmas Site from 3 April 1999 when backwatering occurred

The doppler meter was reinstalled in December 1999 but due to damage by rats no data were recorded until late January 2000. The depth and velocity from the recorded events when backwatering occurred in the 1999-2000 wet season showed a similar pattern to the single event recorded in the previous wet season.

3.4.2.2 Runoff from the Palmas site: 1999-2000

The discharge measured in the Palmas Site flume in the 1999-2000 wet season displayed a very different pattern from that of the previous year. Four large runoff events were caused by high rainfall events that in turn caused peak runoff rates of up to 100 L/s to discharge through the field flume. Four smaller rainfall events between 15 and 19 of February 2000 caused peak runoff rates of around 35-40 L/s (Fig 3.24).

The runoff recorded in the four large events may have been caused by runoff from fields upstream in the catchment entering the main study site field and discharging through the flume. This extra runoff then may have caused the high discharge rates (see Overtopping section below).

The field at the Palmas Site did not appear to be **overtopped** during the four small events between 15 and 19 February 2000 (Fig. 3.24). These events were used later in modelling (Chapter 5) to help calibrate the various runoff models.

The compound rectangular V-notch weir below the field flume at the Palmas Site leaked badly until mid March when the drain dried out and it became possible to seal the weir. The doppler meter measured high velocities but could not accurately measure the low flows. The tail should not have the sudden drop off as recorded by the doppler meter (Fig 3.24).

Hence the "tail" of the hydrograph until after early March 2000 does not accurately reflect the true discharge from the field. During the runoff event the weir was submerged for many hours and only after the Ripple Drain had drained did the weir operate properly. However it was difficult to establish when true free flow was present in the weir and the data from the weir was not included in the calculation of the water balance.

The discharge measured from the Palmas Site flume during the 1999-2000 wet season showed the high rates of runoff caused by extreme rainfall events (Fig. 3.25). The events caused the field to be overtopped with peak runoff rates of over 100 L/s measured in the flume.

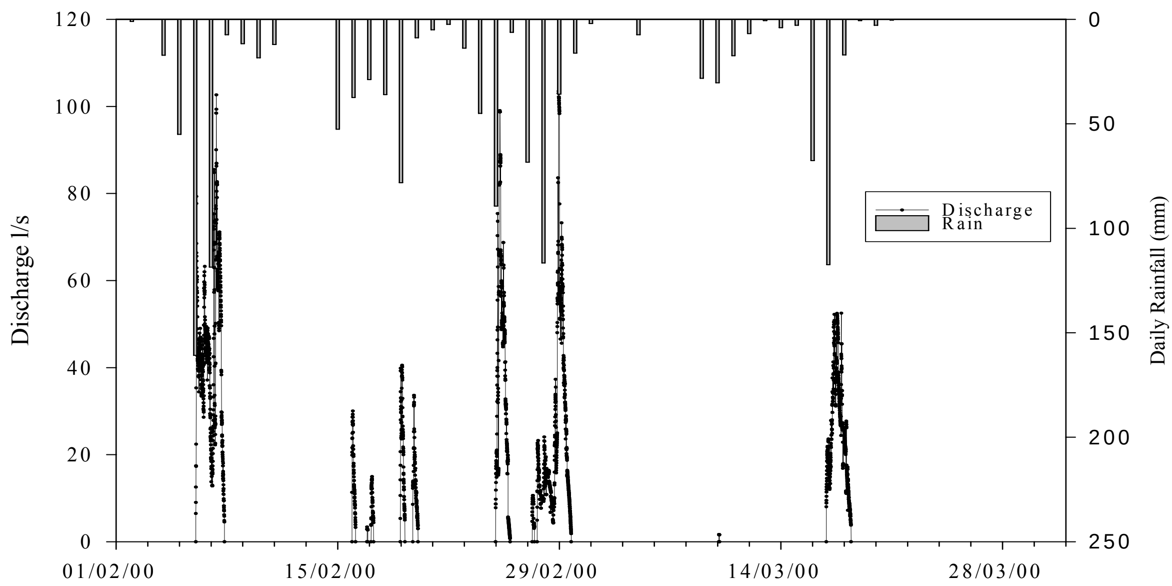


Figure 3.24 Discharge from large field flume at Palmas Site 1999-2000

- *Overtopping*

Overtopping of the field site was observed in both measurement seasons, the overtopping was caused by high rainfall in extreme events. The depth of runoff in the field flume was higher than the difference in elevation between the top of the field and the bottom (Fig 3.24). In the 1999-2000 wet season a mass balance was calculated from the discharge measured by the doppler meter. Higher volumes of water were found to have run off the field than fell as rain (Table 3.5) indicating that water from fields above the study field ran onto the field and caused this difference in mass balance.

The 4 regional floods during February and March 2000 caused high runoff depths at the main Palmas site. The peak depth of water measured at the Palmas site flume was 600 mm (Fig. 3.25). This depth was higher than the elevation of top of the field showing that water from higher in the catchment may have entered the field, discharged through the field flume and backed up through the flume.

Table 3.5 Measured discharges through the Palmas Site field flume for the four regional floods in the 1999-2000 wet season

Date	Discharge (mm)	Rain (mm)
4/2/2000	666	347
25/02/2000	311	134
27/02/2000	468	257
16/03/2000	349	231

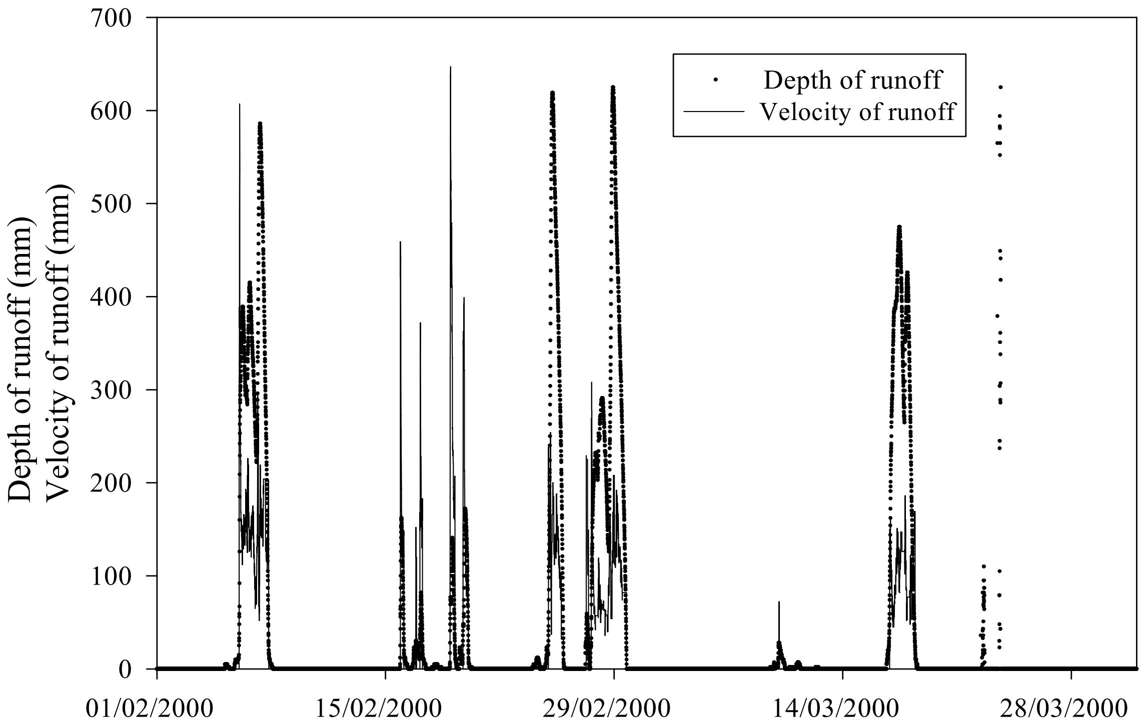


Figure 3.25 Measured depth and velocity of runoff from main field flume at the Palmas site 1999-2000

- *Rating Curve*

The water depth measured in the large Palmas field flume in the 1998-99 wet season could not be used to calculate discharge from the field (Section 3.3.2) as a consequence of the water backed up from Ripple Drain submerging the flume. However as the doppler meter had recorded the water velocity and depth for one event on 3 April 1999 it was thought that these data could be used to develop a **rating curve** for the flume (Appendix B). The rating curve was used to calculate discharge from the measured flume depth and from the large field flume at the Palmas site for the 1998-99 wet season. The rating curve could then be used to determine the volume of runoff for individual rainfall events and the volume of runoff could then be used to estimate a surface water balance (Section 3.4.3).

The water velocity and depth data collected from the event in April 1999 was plotted and a logarithmic function was fitted to the data (Fig 3.26A). There is a relationship between height of the water and the volume of discharge (Fig. 3.26A). There is also evidence of hysteresis in the system as the upper points of Figure 3.26A show the rising limb of the rating curve while the lower points of figure 3.26A show the falling limb of the rating curve. The effect of the hysteresis on the rating curve was measured by fitting separate relationships for the rising limb and falling limb (Figs 3.26B, 3.26C respectively).

A logarithmic function fitted the entire data set reasonably well with an adjusted r^2 of 0.86 (Fig 3.26). The rating curve for the field flume was used only to determine **total event discharge** from the field. The total event discharge is total volume of discharge from the field or the runoff event. The rating curve was not accurate enough to predict **instantaneous discharge** due to the variations in the discharge. The instantaneous discharge is the rate of discharge at any moment during the runoff event.

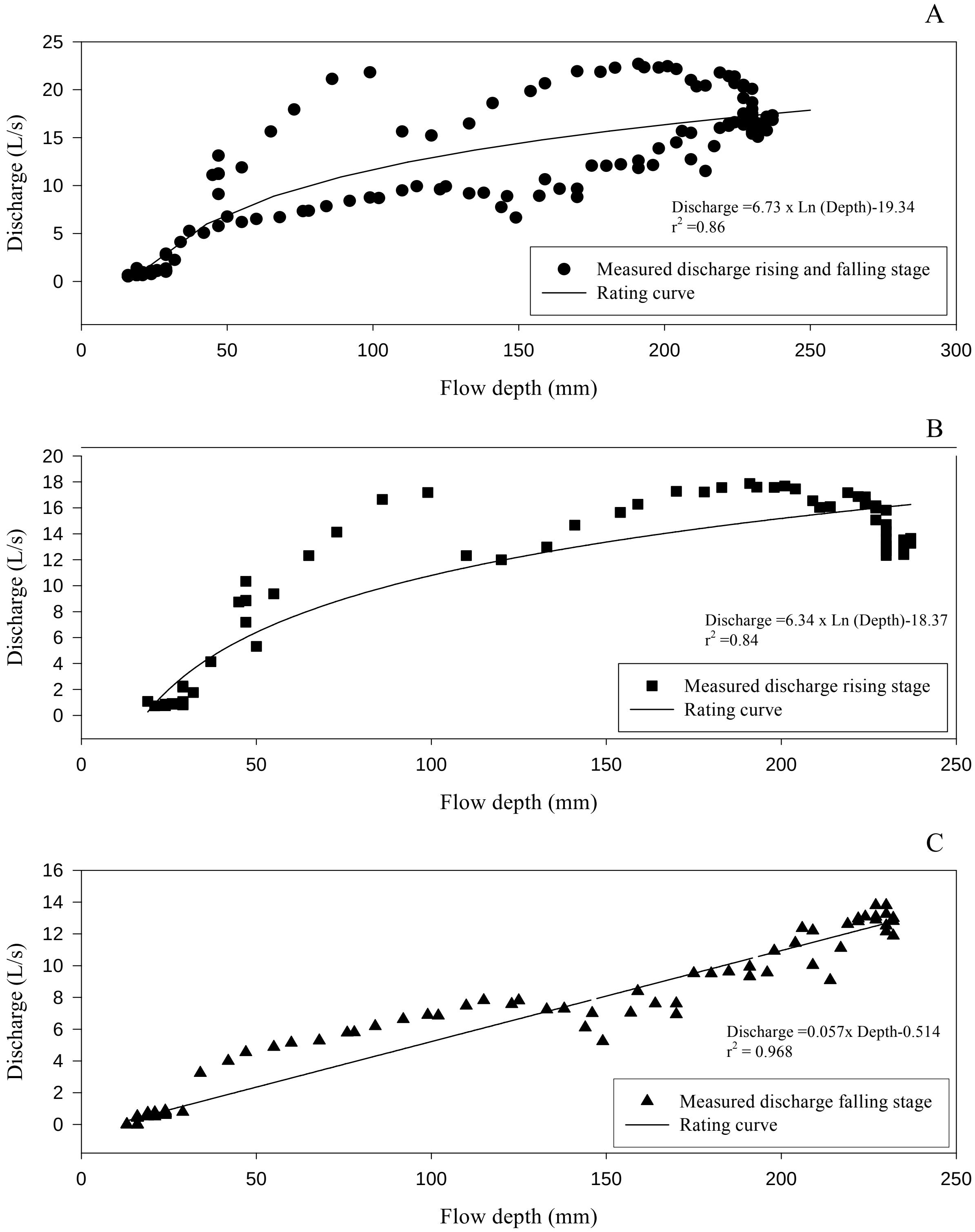


Figure 3.26 Rating curves for the large field flume related to the discharge measured at the large Palams flume on the 3 April 1999 (A: the complete data set with a fitted logarithmic function, B: the rising limb with a fitted logarithmic function, C: the falling limb with a fitted linear function. Discharge measured in L/S and flow depth in mm).

To test the accuracy of the rating curve, the measured discharge was compared to the predicted discharge for the 3 April 1999 event. The measured discharge was 0.38.6 mm compared to the predicted discharge of 46.94 mm (Table 3.6).

A logarithmic relationship fitted the rising limb data well with a $r^2 = 0.84$ (Fig. 3.26B). A linear relationship was fitted to the falling limb of the rating curve which also fitted extremely well with $r^2 = 0.968$ (Fig. 3.26C). When used separately the falling and rising limb relationship improved the accuracy of the prediction of runoff but did not justify the extra effort required.

The overall rating curve (Fig 3.26A) was used to calculate the 1997-98 and 1998-99 discharge from the flume. This figure was then incorporated into the water balance of the field (section 3.4.3). The volume of discharge from each event, as calculated by the rating curve, was compared to the volume of discharge as determined by the models used in Chapter 7 (Table 3.7), and the determination of the surface water balance, as it was the only measured data available.

3.4.3 Surface water balance

The surface water balance for the field can be developed for the 1998-99 wet season and periods of the 1999-2000 wet season. Two methods were used to determine the runoff component of the surface water balance, one method summed the individual runoff events and then summed to calculate the total event discharge (Table 3.6). The other method calculated the discharge for the field by applying the rating curve to the whole of the recorded depth record from the field flume for the 1998-99 data.

The discharge volume was only measured for one event during the 1998-99 wet season. The volume of discharge for the other events were calculated by the rating curve developed above, modelled by Storm Water Management Model (SWMM) (Storm Water Management Model 1995) and the Unit Hydrograph (Chow *et al*. 1988) (Table 3.6). Both models are explained in detail in Chapter 5.

The field was overtopped 4 times through the 1999-2000 wet season and there was a small period between 15 and the 19 February when the row and water furrow discharge was accurately measured. These data were used to partition the runoff into the volume of flow that was discharged from the rows, and the volume of flow that was discharged from the water furrows.

3.4.3.1 Calculation of the discharge for individual events from the main field flume during 1998-1999

The four sub headings in Table 3.6 indicate how the discharges for the individual runoff events were determined. The rating curve, the unit hydrograph, or Storm Water Management Model (SWMM) were used to predict the individual runoff events and then summed to determine the total runoff for the 1998-99 wet season.

The total amount of runoff from the field was calculated by summation of the individual events calculated by the three different methods. The was about 110 mm difference between the runoff determined from the unit hydrograph as compared to the runoff measured by the rating curve. This is due to one runoff event 12/02/1999 in which the unit hydrograph predicts 242 mm or 106 mm more runoff than the rating curve, however only 160 mm fell (Table 2.1) in this rainfall event. Heavy rainfall occurred over 10 hours and this may have caused the unit hydrograph to overestimate the total as the unit hydrograph was developed to simulate a standardised input rainfall excess (Pilgrim 1993). Discounting this one event the three methods gave similar results which suggest that any of the three methods can be used to calculate the discharge of the field from the rainfall data (Table 3.6).

Table 3.6 Comparision of methods to determine event discharge

Date	Event discharge (mm)			
	Rating curve	SWMM	Unit Hydrograph	Measured
12/12/1998	52.65	64.50	68.63	-
06/01/1999	113.09	132.96	120.48	-
19/01/1999	43.57	38.34	48.45	-
12/02/1999	135.75	128.67	241.98	-
15/02/1999	79.76	90.66	89.13	-
27/02/1999	47.34	51.99	45.25	-
06/03/1999	32.95	60.48	55.33	-
08/03/1999	79.25	50.85	43.23	-
09/03/1999	52.38	53.16	38.15	-
11/03/1999	23.45	20.64	35.00	-
25/03/1999	13.33	9.36	6.83	-
03/04/1999	46.94	59.49	38.15	38.6
Total	720	761	830	

3.4.3.2 Calculation of the discharge from the main field flume for the all the 1998-99 wet season

The discharge for the field was then calculated by applying the overall rating curve to the whole of the depth record from the field flume for the 1998-99 data and not just the individual events. The application of the rating curve to the whole data set confirmed whether any events were missed in the determination of the field discharge. This application of the rating curve found that 853 mm of runoff from the large field flume during 1998-99 wet season was measured (Table 3.8). The summation of the individual events found 720 mm was measured (Table 3.6). This additional 133 mm/ha of runoff was unaccounted for when the rating curve was applied to the whole data set. This extra runoff may be due to the isolation of the individual events. When the individual events were selected from the data set, an end point was chosen when it was assumed any extra runoff was insignificant. This process by default will reduce the volume of runoff measured.

3.4.4 Calculation of field runoff event characteristics

The 1998-99 discharge events were modelled using SWMM and the peak discharge, total volume and recession coefficient (τ) (Post and Jakeman 1996) were calculated (Table 3.7).

It is shown in Section 5. 5.1 that these events could be modelled by assuming a Manning's n of 0.1 in SWMM. A similar procedure was performed on the measured discharge events for the 1998-99 and 1999-2000 wet season (Table 3.7). The peak run off rates recorded in the large field flume ranged from 13 L/s/ha to 40 L/s/ha (Table 3.7). This figure is eight times higher than the peak design volume of the drains of 5 L/s/ha recommended by Cameron McNamara (1984).

The velocity of the runoff measured at the large field flume at the Palmas site ranged from 0.3-0.65 m/s. The recommended range is 0.3-0.7 m/s to prevent channel scour (Cameron McNamara 1984). These higher velocities have led to observed channel erosion and high exports of suspended sediment from this field (F. Visser pers comm).

The recession coefficient (Post and Jakeman 1996) was calculated for all the events (Table 3.7). The coefficient ranged between 1.2 to 7.6 hrs, suggesting that the length of inundation from these rainfall events was short for this field.

Table 3.7 Event runoff measured in Palmas Site field flume from 1998-99 and 1999-2000 wet seasons

Date	Rain (mm)	Peak Runoff Depth (m)	Velocity (m/s)	Discharge (L/s/ha)	Recession coefficient τ (hr)	Discharge (mm)	Runoff Coefficient
12/12/98	74			24*	3.7*	64.5*	0.87*
06/01/99	153.5			18*	3.3*	132.9*	0.87*
19/01/99	43			27*	4.9*	38.3*	0.89*
12/02/99+	159.5			37*	5.6*	128.37*	0.80*
15/02/99	77.25			19*	4.3*	90.7*	1.17*
27/02/99	56.25			20*	4.2*	51.9*	0.92*
06/03/99	44.5			14*	3.5*	60.48*	1.36*
08/03/99	60.5			19*	4.3*	50.9*	0.84*
9/03/99	46.5			14*	4.3*	53.2*	1.14*
11/03/99	33			13*	4.0*	20.6*	0.62*
25/03/99	25.5			26*	1.2*	13.3*	0.52*
02/04/99	53.5	0.237	0.28	18	7.6	40.0	0.75
15/02/00	54.2	0.162	0.46	30	2.7	31.7	0.58
17/02/00	19.0	0.082	0.37	15	1.9	12.6	0.66
18/02/00	58.7	0.141	0.65	41	2.4	57.7	0.98
19/02/00	58.8	0.172	0.40	34	4.3	39.7	0.68

+ field was overtopped *modelled (SWMM)

The discharge from the individual events ranged from 12.6 to 132.9 mm. This discharge was used to calculate runoff coefficients for the events. The runoff coefficients ranged from 0.52 to 1.36. The typical range of runoff coefficients for the humid tropics is between 0.4 and 0.6

(Hillel 1998). Only two of the calculated runoff coefficients were within this range, most of the coefficients were higher than 0.6 (Table 3.8).

This high figure suggests that most of the rain that fell ran directly off the field and did not infiltrate the soil. In three events more runoff was recorded than rainfall 15 February 1999, 6 March 1999, and 9 March 1999 (Table 3.7) as indicated by the runoff coefficients for those events. The events that had a runoff coefficients above the range 0.4-0.6 (Hillel 1998) may suggest that either the discharge measurement may be inaccurate, or run on from water draining from higher in the catchment and entered the field and was measured as discharge from the study site.

Table 3.8 Discharge data from Palmas field flume measured during the 1998-99 wet season

	Total rain (mm) Dec 98-Apr 99	Total event discharge (mm)			Total field discharge (mm)
		Rating Curve	UH	SWMM	
Total Runoff	1631	720	830	761	853
Runoff Coefficient		0.44	0.51	0.47	0.52

The total discharge for the field was calculated by each method for the individual events runoff during 1998-99 wet season (Table 3.7). The summation of the individual events was used to calculate the overall runoff coefficient for the field by dividing the total runoff by the rainfall (Table 3.8). The total field discharge (Table 3.8) was determined by applying the rating curve to the whole runoff data set. The area of the field was 1 ha and the discharge is presented as millimetres of runoff from that area.

3.4.4.1 Calculation of the discharge for individual events from the water furrow flumes during 1998-99

Measurement of runoff from within the water furrow experienced the same problems as measurement of runoff from the flume at the main study site. The original 402 mm (sixteen inch) flumes installed for the first wet season were affected by backing up of drain water. The runoff could not flow freely down the water furrow as it was impeded by the overfull regional drainage system.

The flumes were not designed to measure free flow and again the data collected in the first measurement season could not be used. The flumes were modified to measure submerged flow by the addition of a second stilling well in the exit section of the flume (Fig. 3.9). No useable data was collected from the flumes during the 1999-2000 wet season due to rat damage to the depth measurement equipment.

3.4.4.2 Calculation of the discharge for individual events from the row flumes during 1998-99

The recorded flow rate from the rows was too low to be measured by the eight inch flumes installed in the rows (Fig. 3.28). The high peak in Figure 3.28 is from the large flood in February 1999, while the smaller peaks are from the high rainfall events throughout the season. The water did not flow freely from the rows as expected. The low slope and the trash blanket caused the water to back up in the flumes, submerged them and did not allow the flumes to measure the flow rate within the rows.

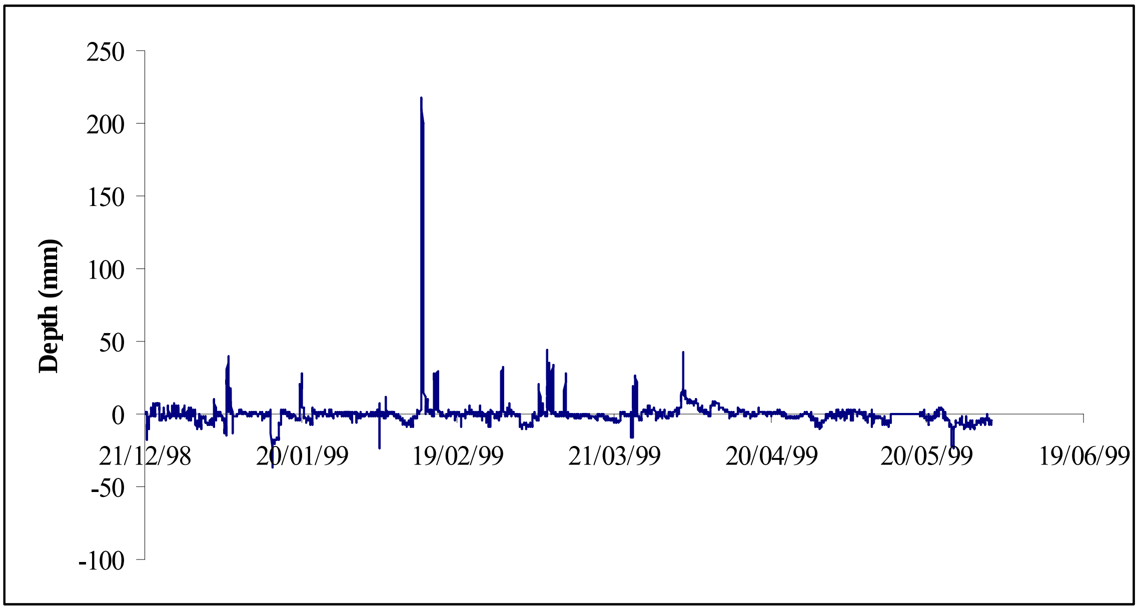


Figure 3.27 Depth of water measured in 201 mm (eight inch) row flume during the 1998-99 wet season

The 201 mm (eight inch) flumes sited at the end of the rows were also too large to measure the flow from the rows. These flumes were also affected by water backing up from the regional drainage system and making discharge measurement impossible (Fig. 3.29).

Figure 3.28 An 201 mm (eight inch) flume at the bottom of the Palmas Site inundated by high rainfall

3.4.4.3 Calculation of the discharge for individual events from the row flumes during 1999-2000

The small flumes placed at the end of the rows were originally designed to measure much higher flows than occurred in the 1998-99 wet season. These small field flumes were redesigned for the 1999-2000 wet season to measure the lower flow rates (Section 3.3.2).

The small in-row flumes were not reinstalled in the second wet season. It was thought that the flumes at the ends of the rows would provide enough discharge data to understand the runoff processes occurring within the field. They were overtopped however, by the extreme events of the 1999-2000 wet season. The weir at the end of the row was damaged by a vehicle in early January 2000 and was replaced late in the same month by an identical weir, small leaks occurred until it was resealed in early March 2000. Small weirs were considered but given the low flows and the low slope this would have had similar problems to the small flumes. In the end no robust methodology was found to measure the flow in the rows in the field.

No useful row discharge data were recorded in the 1998-99 wet season due to the inadequacies of the 402 mm (eight inch) flumes. The only data that was used was recorded by the flumes at the end of the rows. This data was recorded during the 1999-2000 wet season and provided the whole data set. However during this wet season 4 high rainfall events submerged the flumes and no row runoff data were recorded for these events. However, a series of small rainfall events occurred in mid February 2000, which caused low runoff rates, and the row flumes allowed the peak and total discharge for these events to be recorded.

The flumes and weir located at the Lasered Palmas Site recorded no useful data, even during the small events in February. The water from the field drain located at the bottom of the field filled from rain and runoff and submerged the flumes.

Table 3.9 Event flow rates from row flume at the Palmas site

Date	Peak depth (mm)	Peak flow rate (L/s)	Total Discharge (L)
15/02/00	47	0.66	1028
17/02/00	29	0.28	137
18/02/00	51	0.77	2160
19/02/00	45	0.59	920

3.4.4.4 Partitioning of flow between row and water furrow

Runoff was then partitioned between the row and water furrow by using the measured data during the small events of early 2000 (Table 3.10). The individual row discharges were calculated and multiplied by the number of rows in a bed, in this case 14 (Fig 3.14, Table 3.10).

The flow from the rows was compared to the volume of flow measured in the main field flume (Table 3.10). The main field flume measured flow from both water furrow and row (Section 3.3.2). The volume of flow measured by the individual row flumes (Table 3.9) was extrapolated to calculate the discharge of the 14 rows in the bed system.

The volume of runoff that discharged from the field via the row varied from 18% to 36% as a percentage of the total volume of runoff. The higher proportion of runoff via the rows of 36% may have been due to the low quantity of rain of 19 mm that fell in this event on 17 February 2000 (Table 3.10).

The volume of water that discharged from the field via the rows was on average 25% of the rain that fell. Of all the water that discharged from the field only 36% (standard deviation 12%) of the water exited via the rows. The water furrow accounted for the other 64 % even though it was only 15% of the total area. (Table 3.10)

Table 3.10 Partitioning of row and water furrow flow for selected events during 1999-2000

Date	Rain (mm)	Total field discharge (mm)	Row discharge (mm)	Total row discharge (mm)	Total row discharge as % of	
					Rain	Field discharge
15/02/00	54.2	31.7	0.7	9.8	18%	32%
17/02/00	19	12.6	0.5	7.0	36%	54%
18/02/00	59	57.7	0.8	11.2	18%	18%
19/02/00	59	39.7	1.1	15.4	26%	39%
Average					25%	36%

3.4.5 Flow type

Four runoff events were selected to determine if saturation or rainfall excess flow had occurred during overland flow events. The depth of runoff from the flume was matched to the shallow well hydrograph as measured in Section 4.2. The datum for the shallow well data is set at the top of the row, or 100 mm above the interrow which was also 100 mm above the in row flumes. On all occasions the shallow well record showed the watertable either intercepting the soil surface just prior to runoff occurring, or the watertable being within 100 mm of the soil surface. Runoff was generated once the soil was saturated (saturation excess) (Fig 3.29) this observation suggests that the dominant flow type is saturation excess flow and not rainfall excess flow. Rainfall excess flows maybe present in the compacted interrow however shallow wells located in the interrow show the watertable intercepted the soil surface at the time of runoff initiation.

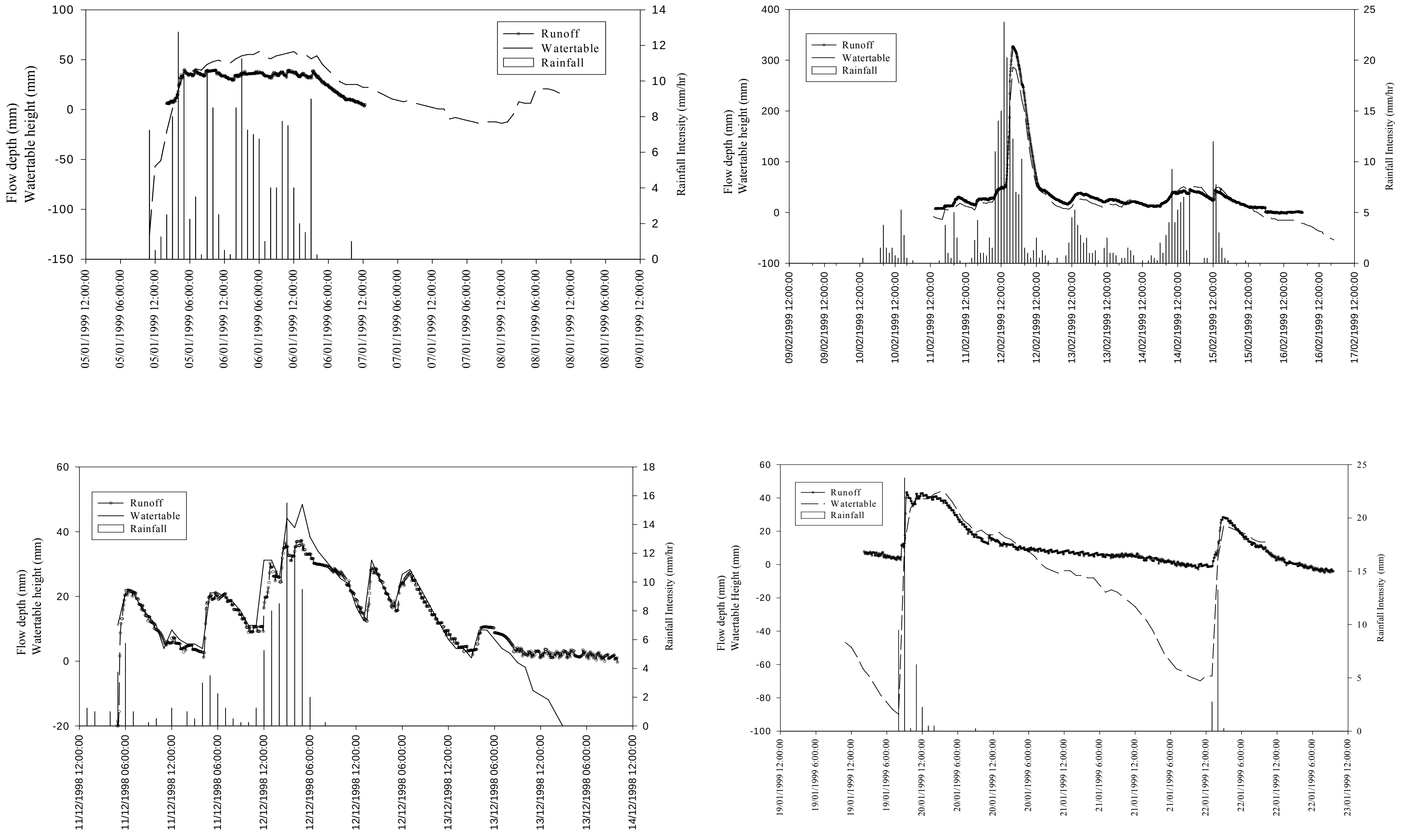


Figure 3.29 Runoff and shallow well hydrographs showing saturation excess flow.

3.5 DISCUSSION AND CONCLUSIONS

3.5.1 Depth discharge

The flow of water through cane trash was successfully modelled by calibration of both the Manning's equation and the generic depth discharge equation (Section 3.4.1). The value of the Manning's n of 0.13 for flow without the trash agrees with other published data on irrigated sugarcane without trash. Raine *et al.* (1997) measured a Manning's n between 0.07-0.15 for flow through a green cane trash blanket.

Smith *et al*. (1990) suggested that the flow through thick vegetation was not well described by the Manning's equation, however they conducted experiments with a minimum depth of water of 0.15 m, somewhat deeper than the maximum flow depth of 0.1 m used in the present study. That lower flow depth may be the reason why the the experimental data fits so well with Manning's equation. An underlying assumption of the Manning's equation is that Vy the product of the water velocity (V) and depth (y), is uniquely related to the resistance value of a particular vegetation cover (Moore and Foster 1990). The thickness of the trash blanket in the present study was 50-100 mm, corresponding to the maximum depth of the water flowing along the rows. Hence, the effect of the trash blanket dominated the response of the flow. If the depth of flow was greater than the thickness of the trash blanket, the trash blanket would influence the flow much less, and the assumption of Vy being uniquely related to the Manning's n would break down as was suggested by Smith *et al.* (1990). As noted in Section 3.3.1 the pump available was not big enough to produce adequate volume of water to test this theory.

The hypothesis postulated by Smith *et al.* (1990) that the Manning's equation could not accurately describe the flow through a thick trash blanket, as viscous forces would dominate, was rejected. The Manning's equation proved to a very robust description of overland flow through a sugarcane trash blanket (Section 3.4).

The observed data fitted the generic depth discharge equation proposed by Turner and Chanmeesri (1984) with an r^2 between 0.77 and 0.99 (Section 3.4.1) but was not used in any predictive capacity. The parameters derived for the generic depth discharge equation, k and α (Table 3.4, Table 3.11), agreed well with the ranges presented in the literature (Maheshwari 1994).

Table 3.11 Summary of the depth discharge equation parameters

Condition	Mannings	Depth discharge		Maheshwari 1994	
	n	α_f	□	flow type	α_f
Trash	0.31	2.66	50	mixed flow	1.67-3.0
Trash	0.31	2.06	10	mixed flow	1.67-3.0
No trash	0.13	1.69	7.9	fully turbulent	1.67
90^o	1.05	3.00	0.0000043	fully laminar	3.00
45^o	2.62	3.00	0061	fully laminar	3.00

The depth discharge equation parameters in general agreed with Maheshwari's (1992) suggestion that the exponent of the depth discharge relationship indicates the type of flow regime (Table 3.11). The exponent for the flow (α_f) on the low slope with trash blanket was 2.66 which may equate to a mixture of both turbulent and laminar flow (Maheshwari 1992). The exponent of 2.06 for the flow through trash on steeper slopes indicates a mixture of both turbulent and laminar flow. When the trash was removed, the flow became more turbulent and the exponent measured was 1.69, which is very close to the value suggested by Maheshwari (1992) of 1.67.

On the flatter slopes, the exponent (α_f) was 2.60 (Table 3.11), which indicates mixed flow (Maheshwari 1992). The value of the exponent (α_f) of 2.06 for flow through trash on slightly steeper slopes indicated mixed flow of both turbulent and laminar flow (Table 3.11). When the trash was removed, the flow became more turbulent and the value of the exponent m became 1.69 (Table 3.11), which is very close to the value suggested by Maheshwari (1992) of 1.67.

The value for the generalized depth discharge equation exponent (α_f), for the flow across the rows, agreed with the theoretical limit of 3.0 (Maheshwari 1992) where the flow was completely laminar (Table 3.11). This matched the field observations of the water as it flowed over the rows; the depth was measured from the bottom of the interrow space and the water flowed around the bases of the sugarcane plants into the interrow space on the lower side. The flow was very tranquil and was visibly retarded by the thick stalks of the cane plants.

The flow of water through cane trash can be successfully estimated by the application of the Manning's equation (Equation 3.5) and the depth discharge equation (Equation 3.7 Section 3.4.1). The Manning's n calculated in the present study agrees with results from a similar study (Raine *et al.* 1997) which determined a Manning's n from irrigated sugarcane fields with green cane trash blanket present. The exponents of the depth discharge equation calculated in the present study agreed with the theoretical values proposed by Mahashwari (1992) (Section 3.4.1).

3.5.2 Runoff

The use of simple stage height recorders, such as flumes or weirs, to measure discharge rates in this environment requires review. In most cases in the present study these structures were not appropriate to measure the type of flow created in this environment. Low relief slopes and non-integrated drainage design, coupled with high intensity and high volume of rainfall restricts the free movement of water from low lying fields. The assumption underlying all simple stage recorders is that there is a unique hydraulic head-discharge relationship. This assumption assumes the water is in the state of critical flow, and that any downstream wave or pressure disturbances cannot travel upstream at anytime. If submerged flow occurs, then additional information, such as the height of the tail water, is required to measure the rate of water flow through the structure. As the structures were present from a previous study they were used to provide a known cross section to allow accurate determination of discharge from the measured velocity acquired by the doppler meter.

The inadequacies of these structures became apparent during the course of the present study however a significant amount of money had been spent on equipment for these devices. However, some useful data was recorded by these structures and the recommendation is to be careful of the about the placement of the structures and the subsequent interpretation of the data measured from these structures.

The velocity of the water measurement by discharge meter showed that the runoff from the Palmas Site is dominated by two distinct phases. From the initiation of runoff to 1 hour after the peak rainfall, the runoff was in a state of free flow as the drainage system filled from the runoff from the surrounding fields and hills. After this, the flow changed to submerged flow as runoff became restricted by drainage impedance or the slow dissipation of drainage water into the overfull drainage system.

3.5.2.1 Surface water balance

The surface water balance of the field showed that the water furrow acts as a preferential pathway for runoff. The surface water balance reveals that, on average only 36% of the runoff from the field exits by the rows. The water furrow allows high volumes and rates of water to enter the drainage system quickly (Table 3.10). Although the area of rows is about 87% of the total catchment and the other 13% is the water furrow, only 36% of the runoff leaves via the rows. The majority of the runoff (64%) leaves the field via the water furrow.

3.5.3 Overland flow type

Saturation excess flow appeared to be the dominant surface hydrological mechanism for removal of surface water from the studied sugarcane field (Section 3.4.2).. Hence the control of the watertable will also have a major impact on the discharge characteristics of the field and the period over which the field is inundated. The determination of flow type means that the dynamics of the watertable becomes very important in the control of the inundation of the field. The mechanisms that control the dynamics of the shallow fluctuating watertable are discussed in Chapter 4.

CHAPTER 4 WATERLOGGING

4.1 INTRODUCTION

The sugar industry has recognized that if a watertable occurs at a depth of less than 0.5 m in the soil then the field is defined as waterlogged (Rudd and Chardon 1977). A shallow watertable can be caused by water perched on a restrictive layer, or by the shallowest **aquifer** in the soil profile rising to or above the soil surface. Where an aquifer may have a recharge zone at some distance from the shallow watertable, the perched watertable is assumed to be recharged from the immediate soil surface, additionally a perched watertable typically overlies a clay layer of lower hydraulic conductivity while an aquifer is usually defined as a porous geological formation that transmits water (Hillel 1998).

The occurrence of shallow watertables within sugarcane fields in the humid tropics is widespread (Rudd and Chardon 1977; Tait 1995). Sugarcane has been shown to be very tolerant of waterlogged conditions (Roach and Mullins 1985; Deren *et al.* 1991; Srinivasan and Batcha 1992; Deren and Raid 1997). However, waterlogging by shallow fluctuating watertables has long been recognized as a major constraint to the productivity of the sugarcane industry in the Lower Herbert Valley (Tait 1995). The effect of waterlogging on the growth and yield of sugarcane has been examined in Section 1.2.8.

A reason for the incorporation of water furrows into the field design has been to control shallow watertables (D. Horsley, pers. comm.). A typical field design incorporates a water furrow every 20-25 m i.e. every 14-16 rows. The water furrows are approximately 0.4 m deep and 3 m wide at the top with a triangular cross section. The influence of the water furrows on the shallow watertables and their role in the water balance and the regional drainage system are poorly understood. The assumption is that water furrows drain the watertables by the hydrological process of interflow.

Interflow can be defined as water that has infiltrated into a soil and moves laterally through the upper soil horizons towards ditches or streams as shallow, perched groundwater (less than 1 m below the soil surface) above the main groundwater level (Ritzema 1994). Interflow will only occur if there is a gradient in watertable elevation caused by a ditch or drain to be lower than the watertable (Ritzema 1994).

Several questions arise in determining the influence of the water furrows on the dynamics of the watertable. If watertables are not present in low lying sugarcane fields then removal of water furrows from the field design could be implemented without any negative impacts on productivity. If the shallow watertables negatively affect the productivity of sugarcane then what role do the water furrows have in the dynamics of the watertable? On the other hand, do water furrows at the current spacing influence the dynamics of the shallow fluctuating watertable?

The research reported in this chapter outlines methodology for measuring the dynamics of the shallow watertables in a low lying sugarcane field, and quantifies the flux of interflow from the watertable to the water furrow. The amount of water that left the watertable as interflow was measured. The quantification of interflow enabled a water balance to be constructed and the influence of the water furrows on the watertable to be assessed.

4.2 THEORETICAL BACKGROUND

4.2.1 Watertable dynamics

Two types of shallow watertables could occur at the study site namely a perched or a phreatic watertable. A perched watertable develops when a soil layer of higher hydraulic conductivity overlies a layer of soil of suitably lower hydraulic conductivity. At some time after infiltration has started, the wetting front will reach the layer of lower conductivity and the infiltration rate will be controlled by the hydraulic conductivity of the lower layer. If infiltration continues at this lower rate and the soil above has a suitably low hydraulic conductivity then a positive pressure head (a perched watertable) may develop above the layer of lower conductivity (Hillel 1998).

The other type of watertable that may be present is groundwater that is within an unconfined aquifer or **phreatic** aquifer is free to fluctuate and find its own equilibrium with the atmosphere. This groundwater may periodically intercept the soil surface (Hillel 1998).

4.2.2 Interflow

If either shallow watertable is present, the water will move laterally under gravity towards a ditch or drain that is lower in the landscape. The movement of the water through the soil matrix can be described by a horizontal flow equation (Marshall *et al.* 1996) as follows:

$$\frac{\delta\theta}{\delta t} \approx \frac{\delta}{\delta x}\left[K_H\left(\frac{\delta H_p}{\delta x}\right)\right] \qquad \text{Equation 4.1}$$

Where
K_H is the horizontal saturated hydraulic conductivity (m/hr)
θ is the volumetric moisture content (m^3/m^3)
H_p is the pressure head (m)
t is the unit of time (hr)
x is distance between the two points of interest (m)

The rate at which the water moves through the soil to a drain can be estimated by Darcy's Law. The estimated rate can be combined with the Laplace equation to estimate the flux (Hillel 1998). A simpler method to determine the flux was put forward by Dupuit (1855, cited in van Shilfergaarde 1974). Dupuit made two assumptions: in a system of gravity flow, all streamlines that flow towards a shallow sink are horizontal, and the velocity of flow along those streamlines is proportional to the slope of the watertable but is independent of depth (Dupuit 1855 cited in van Shilfergaarde 1974).

A literal application of the Dupuit assumptions shows that no flow will occur, as the vertical velocity of flow in the horizontal plane will be constant and as the flux exits the soil matrix at a seepage face the flux will have no velocity (Fig. 4.1). If this assumption of zero velocity is extended across the plane within the soil matrix then there is no velocity across the plane. Hence, if the soil water has no velocity on the seepage face the soil water will have no velocity everywhere and no velocity means no vertical flow (Fig. 4.1). No vertical flow results in the slope of the watertable being zero hence, no horizontal flow (van Shilfergaarde 1974). This understanding of the behaviour of saturated water flow under the influence of drains was critical to the development of agricultural drainage theory (van Shilfergaarde 1974) and underpins the theoretical basis of the Youngs model (Youngs 1989) used in this thesis.

Forchheimer (1904 cited in van Shilfergaarde 1974) assumed that the saturated hydraulic conductivity (K) combined with the slope of the watertable in both the vertical (dh/dx) and horizontal (dh/dy) plane could be substituted as the velocity component in the Dupuit assumption. This assumption, now called the **Dupuit-Forchheimer** assumption has proved to be robust in the prediction of watertable heights with an error of only 5% (Youngs 1985).

Kirkham *et al.* (1974) showed it was unsafe to use the Dupuit-Forchheimer theory to predict tile drain spacing due to the inability of the theory to predict a zone of seepage leading to an overestimation of the effectiveness of the drains, which in turn led to a prediction of too wide a drain spacing. The Dupuit-Forchheimer theory is safe for open drains such as water furrows and those shown in Figure 4.1 (Kirkham *et al.* 1974). The watertable predicted by the Dupuit-Forchheimer theory is shown as an ellipse in Figure 4.1(Kirkham *et al.* 1974).

Hooghoudt (1940, cited in Youngs 1985) included the effect on the drainage by **radial flow**, the flow below the base of the drain flowing towards the drain, by the introduction of an **equivalent depth** (d) of soil. The equivalent depth recognizes the fact that the watertable is higher, with an impermeable layer present than it would be, if the soil were infinitely deep (Hillel 1998). The resistance to flow of this layer is assumed to be the sum of the horizontal and radial resistance to flow down to the impermeable layer. This assumption allows the streamlines to converge at the drain.

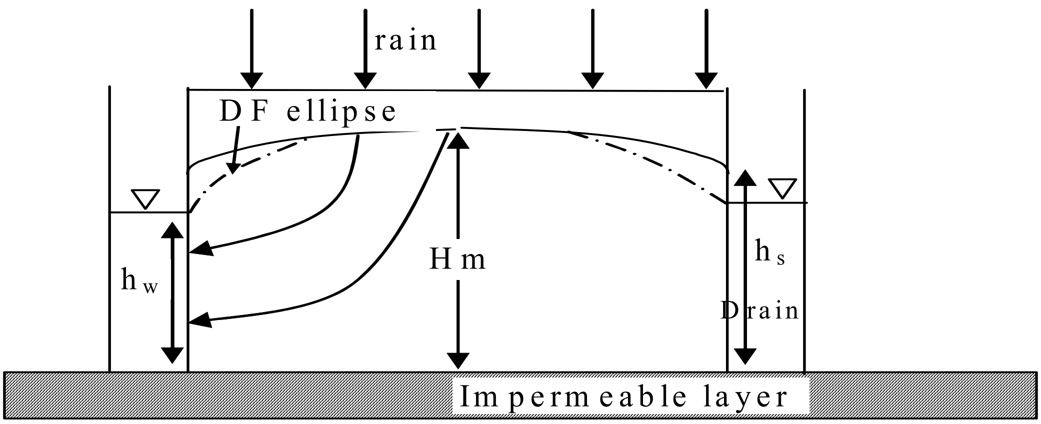


Figure 4.1 Schematic drawing of the Dupuit-Forchheimer (DF) drainage theory showing theoretical streamlines (Kirkham *et al.* 1974). Where Hm is mid height of watertable (m), h_w is height of water in ditch (m), h_s is height of seepage face above impermeable layer (m), and h_s-h_w is zone of seepage (m)

The Hooghoudt equation (Youngs 1985; Hillel 1998) is expressed as:

$$\frac{H_m}{D} = \left[\frac{-d_e}{D} + \sqrt{\left(\frac{d_e}{D}\right)^2 + \frac{q_{sr}}{K}} \right] \qquad \text{Equation 4.2}$$

where
H_m is the mid height of the watertable from impermeable layer (m)
2D is the drain spacing (m)
d_e is the equivalent depth of the soil (m)
q_{sr} steady rainfall rate (m/hr)
K is the saturated soil hydraulic conductivity (m/hr)

The equivalent depth is calculated from the equation

$$\frac{d_e}{D} = \frac{1}{\dfrac{\left(\dfrac{D-d}{\sqrt{2}}\right)^2}{Dd + \dfrac{4}{\pi}\ln\left(\dfrac{d}{\sqrt{2r_0}}\right)}} \qquad \text{Equation 4.3}$$

where
d_e is the equivalent depth of the soil (m)
2D is the drain spacing (m)
d is the depth to the impermeable layer (m)
r_0 is the radius of the drain (m)

An optimum for the radius (r_0) can be developed using a **hodograph** analysis (Lovell and Youngs 1984), and then application of the optimum radius for a given q/K can be fitted to the power relationship (Lovell and Youngs 1984):

$$\frac{H_m}{D} = \left(\frac{q}{K}\right)^{\frac{1}{\beta}} \qquad \text{Equation 4.4}$$

where

$$\beta = 2\left(\frac{d}{D}\right)^{\frac{d}{D}}, 0 \le \frac{d}{D} \le 0.35$$ Equation 4.5

$$\beta = 1.36, \frac{d}{D} \to \infty$$ Equation 4.6

Equation 4.4 may be rearranged to:

$$K = \frac{q}{\left[\frac{H_m}{D}\right]^{\beta}}$$ Equation 4.7

Where
K is the saturated hydraulic conductivity (m/hr)
q is the steady rainfall rate (m/hr)
Hm is the mid height of the watertable above the impermeable layer (m)
D is the half drain spacing (m)
β is a shape factor

Equations 4.1 and 4.4 can both be used to determine the seepage rate from the watertable. Equation 4.4 is a simpler method and can be used by assuming that q (steady rainfall rate) is equivalent to the seepage rate from the soil (Youngs 1985). This is based on the Dupuit-Forchheimer assumption and that the watertable drains to open ditches. The use of the horizontal flow equation (Equation 4.1) can also be used, but the approach developed by Youngs (1985) appears to be even simpler while producing similar results. For the present study the approach developed by Youngs (1985) is used for the measurement and modelling of current field designs. The Darcian flow approach is used in exploring possible field designs in Chapter 7. To use both relationships, soil hydraulic properties such as the saturated hydraulic conductivity, the moisture retention curve, and the equivalent depth must be known.

4.3 METHODS AND MATERIALS

4.3.1 Determination of soil hydraulic properties

The hydraulic properties of the soil at the Palmas Site were determined to allow measurement of the flow of water within the soil matrix. This allowed a water balance to be constructed for the site and modelling of the dynamics of the watertable.

The measurement of the soil hydraulic properties involved both field and laboratory analyses. Undisturbed soil cores were sampled from the interrows and rows from the site in December 1997 and were subjected to a series of standard soil hydraulic measurements. The undisturbed cores measured 73 mm in diameter and 50 mm in height; 4 replicates were taken for soil moisture retention determinations and 9 cores were taken for separate vertical and horizontal saturated hydraulic conductivity determinations. Two soil pits were dug: one in December 1997 to 0.6 m and soil cores were removed from the individual soil horizons for hydraulic conductivity determination and soil water retention; another soil pit was dug to 1.4 m in April 1999 when single ring infiltrometers were used to measure the infiltration rate of the soil. At both times the location of the soil pits were determined by ease of access, close within 3 m of the edge of the field as sugarcane was growing in the field.

4.3.1.1 Soil moisture retention

Soil moisture retention was determined using tension plates and pressure chambers. The cores were prepared in the laboratory by leveling the bottom surfaces. A filter paper was placed between the soil and the tension plate to aid contact, the cores were held at -60 mm suction and allowed to equilibrate. The suction of –60 mm was chosen instead of 0 mm due to the difficulty of handling saturated soil cores. Equilibrium was determined when there was no change in core weight over a 24-hour period and the final weight was recorded. The suction on the plate was then set at the next level. The suctions used were –0.06 m, -0.120 m, -0.3m and -1.0 m.

The soil cores were placed in pressure plate extractors at 0.03 MPa to determine the lower soil moisture potentials. Once equilibrium was reached, determined by static water level in a burette attached to the pressure chamber, 4 undisturbed cores were collected by insertion of a 30 mm diameter corer 10 mm into the top of the large soil core and placing the subsample on a 0.1 MPa tension plate. The four field samples were dried in a soil oven at 105 ^{o}C. The smaller cores were used to complete the rest of the soil moisture retention determinations. The small cores were placed in a pressure plate extractor and the pressure was set to 0.1 MPa. When the small soil cores reached equilibrium, determined by no change in the water level in a burette attached to the pressure chamber, they were weighed and returned to the pressure chamber. The pressure was increased to 0.3 MPa, until equilibrium was reached and the above process was repeated again at 0.5 MPa, and 1.5 MPa.

The Van Genutchen (1980) soil moisture potential equation versus water content was fitted to the soil moisture data using the following form of the equation:

$$\theta(\Psi) = \left(1 + \alpha(-\Psi)^n\right)^{-m} \qquad \text{Equation 4.8}$$

where
θ is the volumetric moisture content (m^3/m^3)
Ψ is the soil moisture potential (m)
α is an empirical parameter (m^{-1})
m, n are empirical parameters (dimesionless) and $m = 1 - \frac{1}{n}$
and

$$K(\theta) = K_s \theta_*^{\frac{1}{2}} \left[1 - \left(1 - \theta_*^{\frac{1}{m}}\right)^m\right]^2 \qquad \text{Equation 4.9}$$

where
K_s is the saturated hydraulic conductivity

$$\theta_* = \frac{\theta - \theta_r}{\theta_s - \theta_r} \qquad \text{Equation 4.10}$$

where
θ is the volumetric moisture content (m^3/m^3)
θ_s is the saturated volumetric moisture content (m^3/m^3)
θ_r is the residual volumetric moisture content (m^3/m^3)

Volumetric soil moisture was calculated from the wet and oven dried weights of the soil cores, sub-sampled cores, and the known core volumes (Eqn A4.1). The saturated volumetric moisture content (θ_s) was assumed to be the soil moisture content at -60 mm suction and the the residual volumetric moisture content (θ_r) was assumed to be the soil moisture content at 1.5 MPa.

The parameters for the van Genutchen soil moisture retention function, α m, n, were determined by the software program RETC (Simunek 1995). The program required the measured volumetric soil moisture and corresponding suction and used a minimization routine to determine the best fit of the soil moisture retention function.

4.3.1.2 Hydraulic conductivity

Saturated hydraulic conductivity was determined four ways:

- Laboratory falling head measurements (Ford 1997)

Nine large intact cores, 73 mm in diameter and 50 mm high, per soil horizon were sampled from the field. In the laboratory a 100 mm long perspex tube was secured with insulation tape on one end of the core. The cores were placed in a small tank and a solution of 2 mM $CaCl_2$ was added to the tank until it was 10 mm below the top of the extension tube. The cores were left until the levels of solution were equal in each of the extension tubes. The solution in the extension tube was removed with a vacuum pump. A stopwatch was started and the tube was allowed to refill. The solution was removed, the volume determined, and the time taken to refill was noted. Saturated hydraulic conductivity was calculated by the volume of water infiltrating the core over the measured times.

- *In situ estimations: Single ring falling head infiltrometry*

Single ring infiltrometers were used to estimate the saturated hydraulic conductivity of the soil in the field at 4 well defined soil horizons. The horizons were at the 0 cm (surface), 350-400 mm, 1.05-1.10 m, and 1.40-1.45 m, as determined by the soil description (section 2.1.5.3) and the following method was used. These soil horizons are described in Table 2.2. A soil pit was dug and benches of an undisturbed soil with a flat surface were dug at the side of the pit at the top of the four soil horizons. The infiltrometers, 300 mm in diameter, and 150 mm high, were sealed into the soil with wax and then filled with water. A float attached to a depth gauge that measured the water depth. Readings were taken at fixed times from the gauge, and the measured water volume was used to determine the infiltration rate. This was repeated three times per soil horizon.

- *In-situ determination: shallow well data*

In March 1999 there was a period of rain that was sufficient to supply the watertable with enough rain to maintain it at a steady level for ten days but not sufficient to produce overland flow. This enabled the hydraulic conductivity (K_1) of the topsoil to be determined by an empirical relationship (Equation 4.5) that assumes the drains are large enough not to impede flow (Youngs 1985). From the infiltrometer measurements the C horizon was found to be the impermeable layer (H_m). Thus the mid height of the watertable from impermeable layer (H_m) was assumed to be the depth of the C horizon (1.0 m).

- *Rainfall simulation*

A rainfall simulator was developed at CSIRO Davies Laboratory, Townsville with a 4 m high, constant pressure drip tower with 1000 capillary tubes (3 mm diameter) and covered an area of 1 m^2. A constant rainfall rate was applied to the target area (1 m^2) and runoff was measured from the centre of the target area in a sub plot of 600 mm x 200 mm by placement of a metal frame 600 mm x 200 mm around the sub plot. At one end of the frame the runoff was collected and measured.

Prior to the commencement of the experiment, a plastic container placed over the sub plot. The simulator was turned on and allowed to run for 1-2 minutes, the water was collected in the container and measured and the rainfall rate was determined. The simulated rainfall was initiated when the plastic cover was removed. The time to ponding was noted and the runoff volume was collected and measured at one minute intervals from that time. When the volume of runoff per minute became constant it was assumed that the soil had reached the saturated infiltration rate which was also determined by a mass balance approach. The time at which the runoff had become constant was noted and the volume of runoff and volume of water applied was known. The difference between the volume applied and the volume of runoff was the volume of water infiltrated. The rate of infiltration was calculated by dividing the volume of runoff from the time of constant runoff by the time from that point to the end of the rainfall simulation.

4.3.1.3 Specific Yield

The **specific yield** is defined as the amount of water released to the groundwater or absorbed by the unsaturated soil with a unit change of height in the watertable (Youngs *et al.* 1989).

The change in watertable height due to the water released or taken up (the flux) by the watertable can be written, following Youngs *et al.* (1989), as:

$$V_H = S\frac{\delta H}{\delta t} \qquad \text{Equation 4.11}$$

where
V_H is the watertable height (m)
S is the specific yield (m/m)
$\delta H/\delta t$ is the rate of change in watertable height (m/d)

Including the rainfall or evaporation component (Vs) m, the equation becomes

$$V_H = S\frac{\delta H}{\delta t} + Vs \qquad \text{Equation 4.12}$$

The underlying assumption is that the water flux travels vertically between the soil and the watertable and the time taken for this process is smaller than the chosen model time step (Youngs *et al.* 1989).

The specific yield was determined for the drained layer at the Palmas site, the top 1 m that in the present study is defined as the A and B horizon of the soil. This depth was chosen on the basis of the measured infiltration rate of the C horizon. The infiltration rate in this soil horizon was very low as compared to the A and B horizons such that it would restrict water movement and cause the shallow watertable.

4.3.2 Watertable dynamics and interflow

In December 1998 three transects of three shallow wells, were installed in both the Palmas Site (Fig. 4.2) and in the Macknade Site (Fig 2.2). In January 2000 two shallow wells were installed in the Lasered Palmas Site (Section 2.1.5.2.). The aim was to measure the variation in watertable depth width (water furrow to middle of the bed) and along the length of the field.

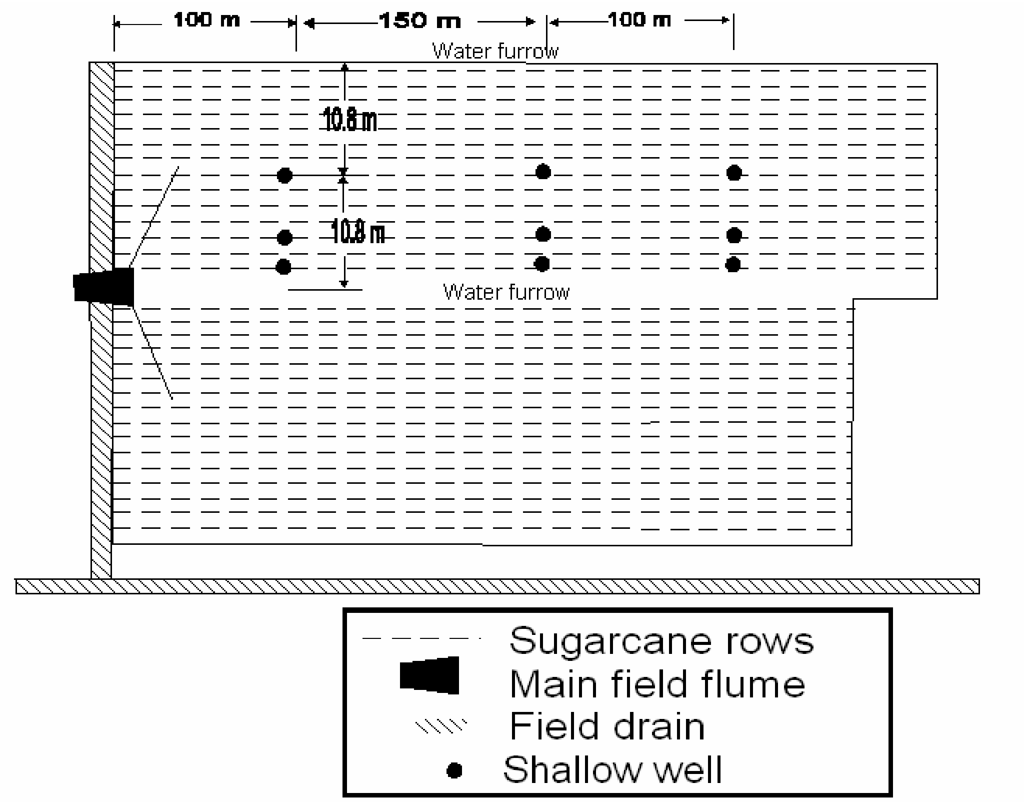


Figure 4.2 Location of shallow wells at the Palmas Site 1998-99.

The site names for the shallow wells were defined by their distance upslope from the main field flume and the row number in which the shallow well was placed. For example site 253 corresponds to the transect that was 250 m from the bottom of the field and the shallow well in the third row.

The 60 mm wells were hand augered to a depth of 1 m and 50 mm diameter, slotted class 6 PVC pipe was inserted into the hole, and the space between the hole and the pipe was back filled with coarse sand to a level 100 mm below the soil surface. The hole around the pipe was then sealed with bentonite and 5 m pressure transducers linked by coaxial cable to a single channel logger were placed 50 mm from the bottom of into the wells. A 1 m length of 50 mm PVC pipe extended upwards from the top of the shallow well and on it was glued a 150 mm

PVC diameter extension, approximately 0.5 m long (Fig. A4.1). This served as storage for the logger and excess coaxial cable.

The above ground extension was attached to the shallow well by a PVC thread joiner to allow the removal of the extensions at harvest. When the extension was removed the shallow well could also be capped to prevent soil entering the well.

The pressure transducers were placed 50 mm above the bottom of the shallow well to avoid mud from affecting their operation. To do this the pressure transducer was lowered into the shallow well until the coaxial cable went slack, the cable was then lifted 50 mm and fixed to the side of the PVC extension. The loggers were set to record the water height every hour. Data for the previous wet season 1997-98 which was recorded by the same method was taken from a single shallow well installed in the Main Palmas site from a previous study (Bohl *et al.* 2000).

4.3.2.1 Location of shallow wells at Palmas Site

The measurement of the depth of the water by the shallow wells defines the shape of the shallow watertable, therefore it was important to locate the wells with regard to the anticipated watertable surface. As the watertable was assumed to be symmetrical only the half the distance between the water furrows (10.8 m) was used as the distance from well to the drain. The present shape of the watertable was modelled by equation 4.13 (van-Shilfergaarde 1974).

$$H^2 = \frac{q_r}{K}\left(2DX - X^2\right) \qquad \text{Equation 4.13}$$

Where
H is height of watertable at position X (m)
q_r is the steady flux which maintains the watertable at a steady state (m)
K is the saturated soil hydraulic conductivity (m/hr)
D is half the distance of the field drain spacing (m)

X is the distance away from the drain (m)

The parameters for the model included the hydraulic conductivity (K) measured in the small intact cores in the laboratory (Section 4.4). The flux to the drain (q) was assumed to be the flow predicted by Darcy's law; if the watertable just intercepts the soil surface at the mid point between the water furrows, the water furrow is assumed to be the drain.

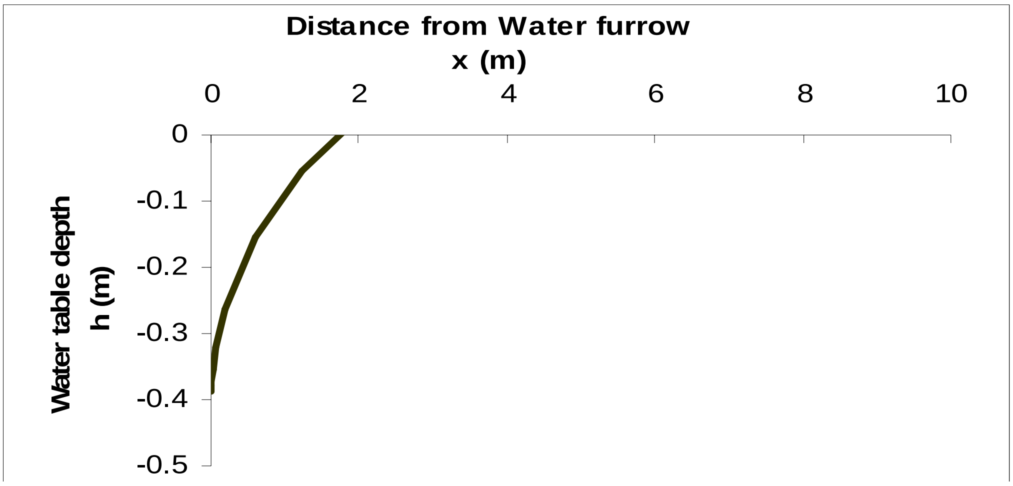


Figure 4.3 Predicted watertable heights for Palmas Site

The model predicted the watertable would intercept the soil surface 0.17 m away from the centre of the drain (Fig. 4.3). From this preliminary modelling, the positions of the shallow wells were installed in a semi-logarithmic pattern from the drain to enable the measurement of the shape of the watertable.

Since the preliminary modelling showed that the watertable would intercept the soil surface about 0.17 m from the drain, it was important place a shallow well between the drain and that point. This result, combined with the fact that the wheels of the sugarcane harvester would also traffic the interrow, and the desire to maintain the wells in an undisturbed state, meant that the spacing of the shallow wells was determined to be 1.5 m apart or multiples thereof, that is correspond with the distance between the rows of sugarcane.

Table 4.1 Location of shallow wells at the Palmas Site

Site Name	Row Number	Distance from water furrow (m)	Distance from field flume (m)	Height of row above water furrow (m)
101	Row 1	1.51	100	0.29
103	Row 3	4.65	100	0.39
107	Row 7	10.8	100	0.49
251	Row 1	1.6	250	0.27
253	Row 3	4.5	250	0.40
257	Row 7	10.8	250	0.50
351	Row 1	1.35	350	0.26
353	Row 3	4.3	350	0.38
357	Row 7	10.25	350	0.43

This meant that the first shallow well was placed in the first row at 1.5 m away from the water furrow, the next at 4.5 m or in the third row, and the third at the mid point between the two water furrows at 10.8 m. (Table 4.1).

4.3.2.2 Location of shallow wells at the Lasered Palmas site

The shallow wells located in the laser-leveled field without water furrows were installed 20 m from the edge of the field (Fig 4.4). The shallow well located at the higher end of the field (Laser Top Peizo) (LTP) was installed as per the method described above. The shallow well installed at the lower end of the field (Laser Bottom Peizo) (LBP) was installed only 0.4 m deep because the clay B Horizon was present at 0.4 m.

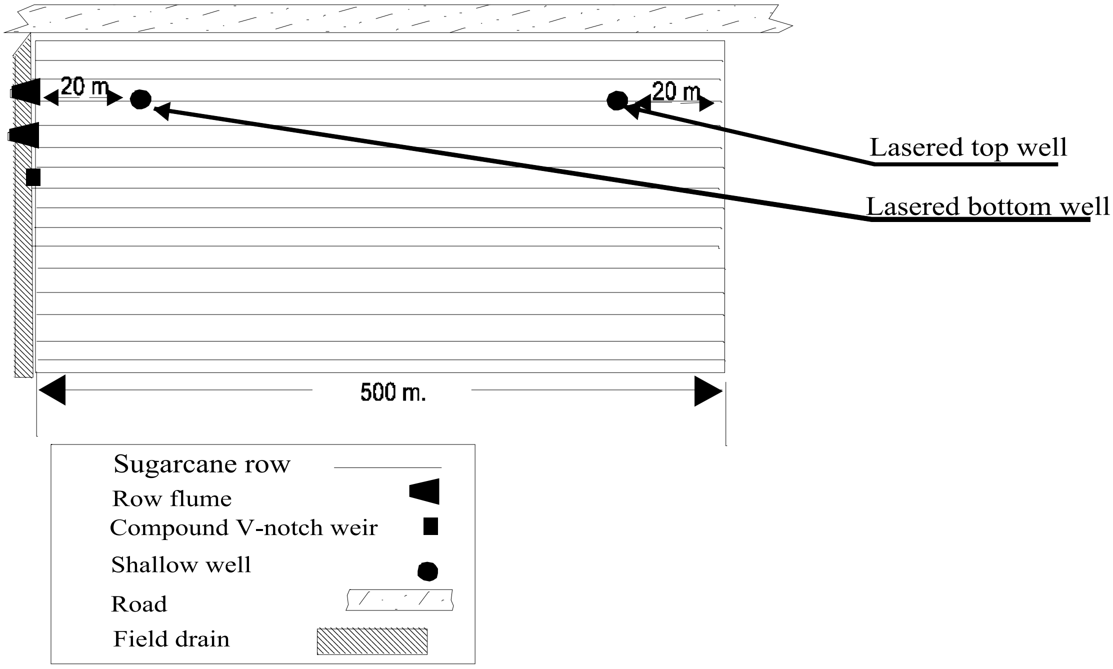


Figure 4.4 Location of shallow wells at the Lasered Palmas Site 1999-2000

4.3.2.3 Location of shallow wells at the Macknade site

The shallow wells located at the Macknade Site were installed in the centre row of the plots (Fig.2.2). The plots measured 20 m x 35 m and two shallow wells were installed on the two flat plots. Due to a shortage of loggers only one instrument was installed on the sloped plot.

4.3.3 Plant growth and yield measurements

The yield of sugarcane in 1997-98 at the Palmas Site was taken from the machine harvested block data recorded by CSR Macknade Mill. The 1998-99 Palmas sugarcane yield was determined by a detailed harvest of three replicates of 10 m rows of cane that was hand cut and weighed; 15 individual stalks were selected and the separate yield components measured. These included **fresh and dry stalk weight**, **fresh and dry live leaf weight**, **fresh and dry dead leaf weight**, **fresh and dry cabbage weight**, **leaf area index**, commercial cane sugar determined using a small press, **brix, pol**, and **fresh and dry fibre weight**. In 1999-2000 10 random samples of 10 stalks were harvested and yield components were estimated on 10 m transects of stalk counts.

4.4 RESULTS

4.4.1 Soil hydraulic properties

4.4.1.1 Soil Moisture Retention

The Van Genutchen (1980) soil moisture retention function was fitted to the observed volumetric soil moisture content and known moisture tensions (Table 4.2). Moisture contents measured at -0.06 m soil water suction were assumed to be the saturated volumetric moisture content (θ_s) and the residual volumetric soil moisture content (θ_r) was assumed to be measured at -150 m soil water suction.

The Van Genutchen (1980) function fits the data for the soil A horizon reasonably well, except for the "dry end" of the retention function (Fig 4.5) with a coefficient of determination of 0.96 (Appendix 2A). The wet end of the retention function shows a relatively sharp air entry point. This may be due to the high number of **bio-pores** present in the cores as the bio-pores drain quickly at low suctions

Table 4.2 Soil moisture retention parametersised in the calculation of the closed form of the Van Genutchen function (Equation 4.8)

Van Genutchen (1980) Parameters	A horizon	B horizon
θ_s (m^3/m^3)	0.388	0.337
θ_r (m^3/m^3)	0.1	0.18
α	1.00	0.33
n	1.00	1.00

The Van Genutchen (1980) function fitted the B horizon data overall better than the A horizon with a coefficient of determination of 0.98 (Appendix 2A). However there was much more scatter in the points around the wet end of the retention function compared to the A horizon.

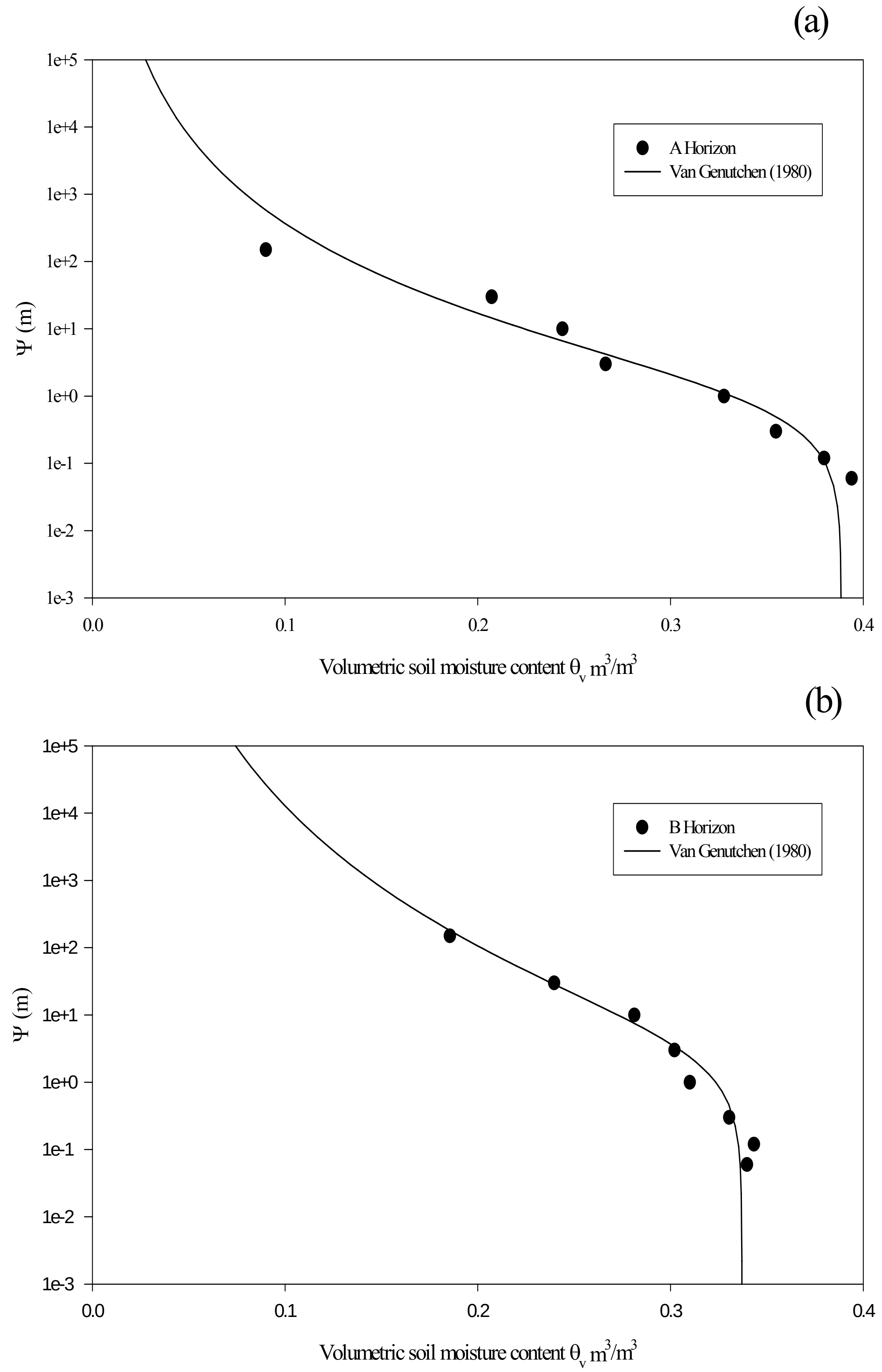


Figure 4.5 A Van Genutchen (1980) soil moisture retention relationship fitted to measured soil properties from Palmas Site (a) A horizon of the soil, (b) B horizon of the soil

4.4.1.2 Saturated hydraulic conductivity

- *Laboratory falling head measurements*

The laboratory determination of saturated soil hydraulic conductivity of the undisturbed cores showed two distinct values (Table 4.3). The compacted interrow had a saturated hydraulic conductivity of 10-16 mm/hr and that of the soil of the porous, well structured row was 38-303 mm/hr. The conductivity of the interrow reflects the impact that traffic has on the structure and porosity of the soil. The row soil had not been trafficked or tilled for 18 months.

Large differences were observed between the vertical and horizontal saturated hydraulic conductivities in the 0-50 mm soil depth range (Table 4.3). This may be a result of the high number of bio-pores that act as preferential pathways to flow. It is unclear though why only the horizontal cores exhibited such high conductivities.

Table 4.3 Soil hydraulic conductivity determined by laboratory measurements on cores from Palmas Site using the falling head method.

Horizon	Depth mm	Horizontal mm/hr	Standard Deviation	Vertical mm/hr	Standard Deviation	Skewness
A Row	0-50	303	33	38	23	1.46
A Interrow	0-50	10	2.5	16	1.0	1.20
B	350-400	34	3	26	11	0.90

The skewness was determined to see how the measured hydraulic conductivities were distributed. It appears that the hydraulic conductivities were normally distributed about a central mean as measured by the values (Table 4.3).

- *Single ring falling head infiltrometry*

Single ring infiltrometer measurements were carried out in April 1999. The results are divided into row and inter row determinations in Table 4.4 and displayed a similar pattern to the small intact cores (Table 4.3) and repeated three times. The saturated soil infiltration rate of the compacted interrow was lower compared to the saturated soil infiltration rate measured in the row (Table 4.4). The measured saturated soil infiltration rate of the impeding layer (C horizon Table 4.4) was low compared to that of the shallower soil.

The saturated soil infiltration rate varied between each determination, as expressed in the standard deviation. The highest deviation occurred in the determination of the saturated soil infiltration rate of the row. The measured infiltration rates for the sandy loam D horizon were very low for the texture of the soil. However, this layer consisted of very compacted sandy loam soil which had packed together very tightly.

Table 4.4 Saturated soil infiltration rates from single ring infitrometer at Palmas site

Horizon	Depth (mm)	Location	Infiltration rate mm/hr	Standard deviation
A	0-50	Inter row	7.23	8.4
A	0-50	Row	147	92.4
B	350-400	-	37	28.4
C	1050-1100	-	0.85	0.2
D	1400-1450	-	0.60	0.4

- *In situ determination from shallow well data*

An average rainfall rate of 4 mm/day was recorded over 8 days (12 March to 20 March 1999), and sustained a constant high watertable (Fig 4.6). This allowed the saturated hydraulic conductivity to be determined *in situ* assuming a steady state equilibrium between the watertable and the flux to the drain. The rainfall was substituted into equation 4.10 as follows:

$$K = \frac{q}{\left[\frac{H_m}{D}\right]^{\beta}}$$ Equation 4.10

Where
q is 0.004 m/day
Hm is 0.5 m
D is 10.8 m
d is 1 m
β is 1.6

Hence K = 0.561 m/day

The saturated hydraulic conductivity (K) = 0.561 m/day is equivalent to 0.023 m/hr or 23 mm/hr.

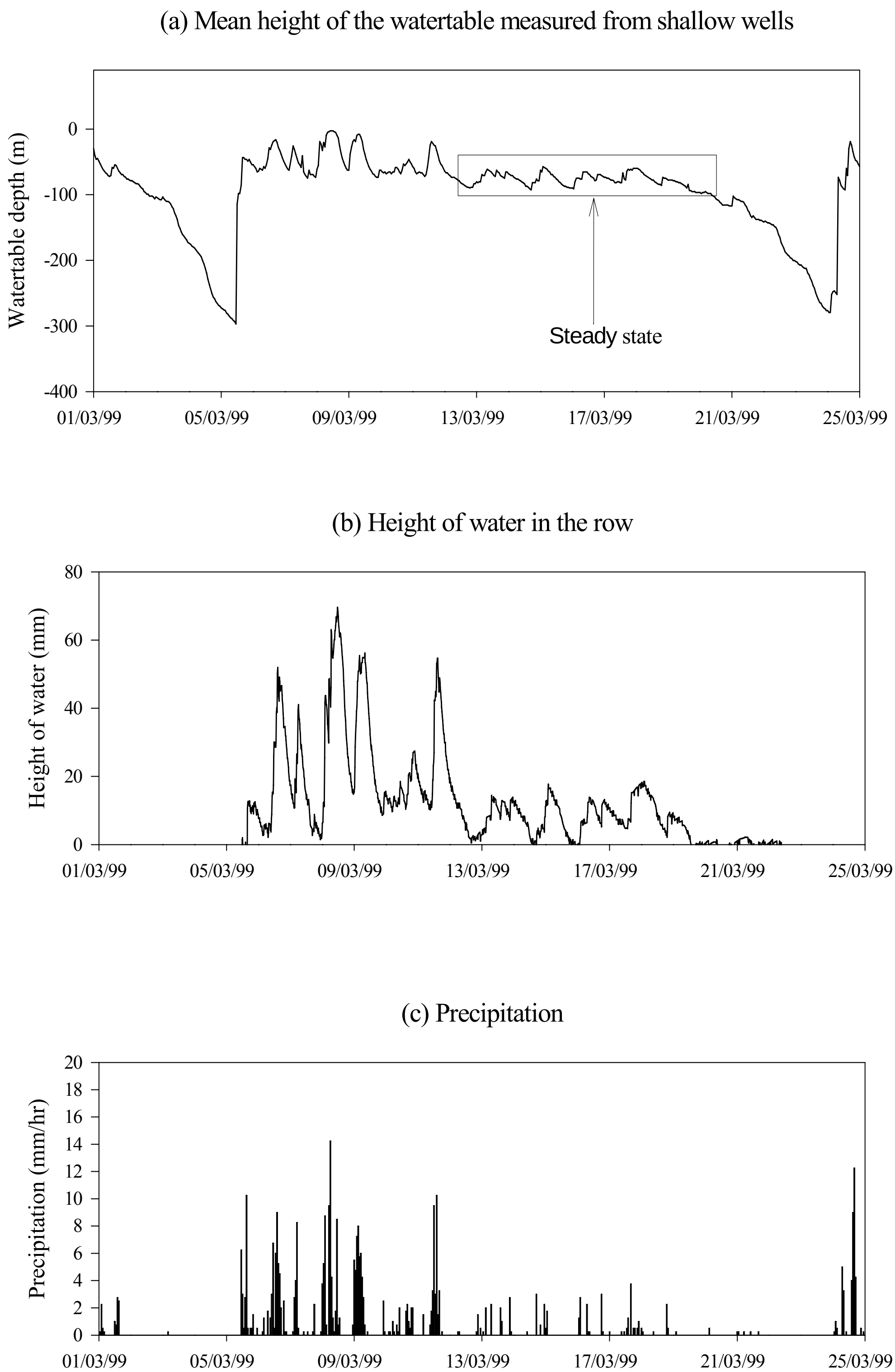


Figure 4.6 Environmental data from the Palmas Site in March 1999 (a) Mean height of watertable measured at Palmas Site, steady state position (in box) used for *in situ* K determination, (b) Height of water in row, (c) precipitation.

The value of 23 mm/hr represents the average saturated hydraulic conductivity of the A and B horizon including both the interrow and row sites. There is an implicit assumption within this approach is that the total environmental flux for each day is equal to the average rainfall rate. This means that no **evapotranspiration** was considered for the period relevant to the calculation.

- Rainfall simulation approach

The hydraulic conductivity measured by the rainfall simulator gave similar results to the other three methods (Table 4.5). The measured saturated hydraulic conductivity under rainfall simulation of the compacted interrow of the Palmas site was higher than the corresponding row sites (Table 4.5).

Table 4.5 Saturated infiltration rate from rainfall simulation

Site	Location	Infiltration mm/hr	Standard deviation
Ratoon	Row	22.1	9.2
	Inter row	10	4.3

- *Summary of hydraulic conductivity measurements*

The different methods of determination for the soil hydraulic conductivity gave values that were very similar (Table 4.6), except for the surface soil of the row determined by the ring infiltrometer. This high figure is thought to be related to the many bio pores present.

The similar values from the separate determinations of hydraulic conductivity showed that the methods used were robust and the measured values were reliable.

Table 4.6 Comparison of soil saturated hydraulic conductivity determinations by different methods of measurement

Method	Depth (cm)	K_{sat} mm/hr
Small ring in laboratory	0.-5	38
Small ring in laboratory	35-40	12.7
Ring infiltrometer	0-5 Row	147
Ring infiltrometer	35-40	37
In situ	0-40	23
Rainfall simulation	Row	22.1

The saturated hydraulic conductivity value selected for the modelling aspects of the present study was taken as 23 mm/hr which was determined by the *in situ* shallow well method. This method measured the infiltration and hydraulic conductivity of the drained layer with minimal disturbance to the site. The only disturbance was installation of the wells 4 months earlier. The watertable dynamics integrated the variability of the infiltration rates and hydraulic conductivity into a single measurement; the change in watertable depth. It was fortuitous, however, that a steady rainfall event occurred to allow the watertable to remain constant while no overland flow occurred. This allowed the watertable depth to integrate the hydrological processes into single measurement.

The saturated hydraulic conductivity determined here was also used in the determination of interflow (Section 4.3.2) and in modelling the watertable response (Section 5.4.1).

4.4.1.3 Specific Yield

Specific yield of the drained layer was determined by the watertable rise from 5 separate rainfall events in the 1998-99 wet season when no overland flow occurred. The watertable data for the determination of specific yield were taken from the shallow well data from the Palmas Site (Fig 4.7). The drained layer was defined for the present study as the A and B horizon (uppermost 1 m of profile).

Equation 4.12 was rearranged (Equation 4.14) and solved for S, the flux term Vs was assumed to be the rainfall, dH was the watertable rise, and dt was the time taken to reach new equilibrium. Due to the short time step , less than 2 hours evapotranspiration was ignored.

$$S = \frac{V_H - Vs}{\frac{\delta H}{\delta t}} \qquad \text{Equation 4.14}$$

The results of the calculation are listed in Table 4.7.

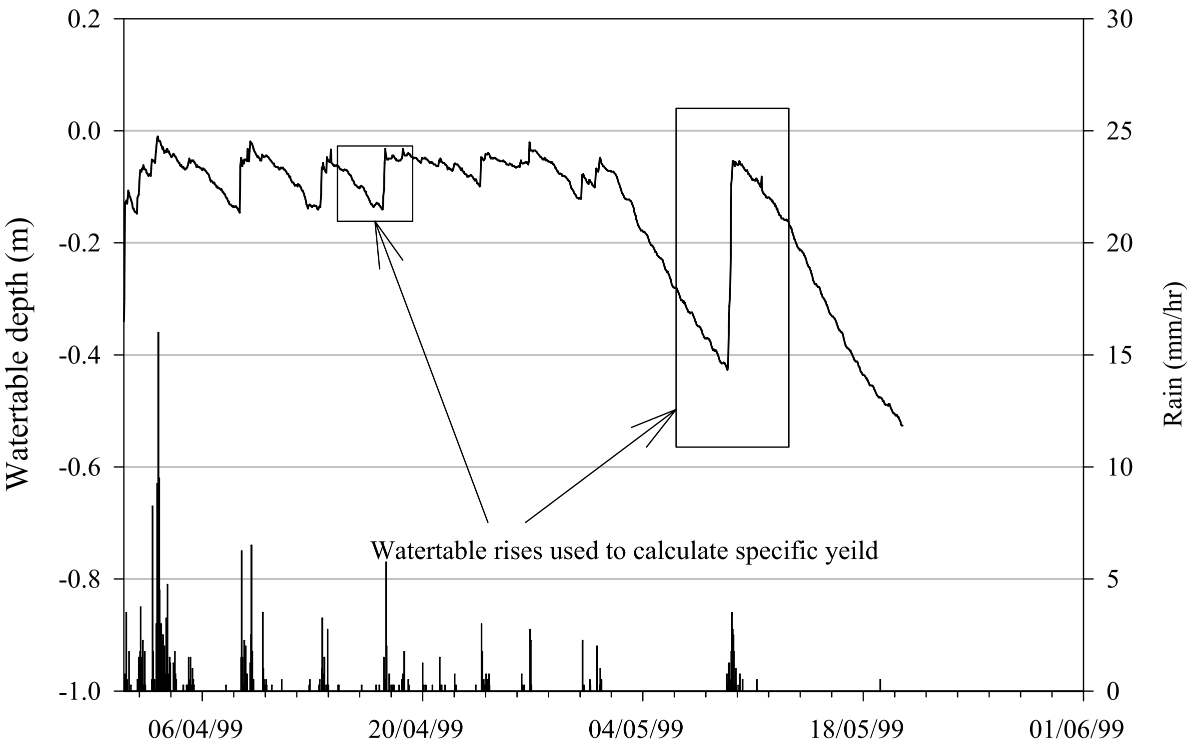


Figure 4.7 Watertable rise in April 1999 at the Palmas Site used to calculate specific yield.

The arithmetic means and the geometric means of the specific yield values were calculated; the geometric mean of the calculations, used when averaging ratios or rates (Steel and Torrie 1981), was taken as the specific yield.

Table 4.7 Specific yield determinations for the Palmas Site using Equation 4.14.

Date	Watertable rise dH (mm)	Time dt (hr)	Rain Vs (mm)	Specific yield S (mm/mm)
21/12/1998	230	4	6.5	0.113
2/01/1999	131	3	4.5	0.103
29/2/1999	258	3	3	0.034
17/4/1999	118	4	8	0.271
9/5/1999	343	5	9.75	0.142
			Mean	0.133
			Geometric mean	0.109

4.4.2 Watertable dynamics and interflow

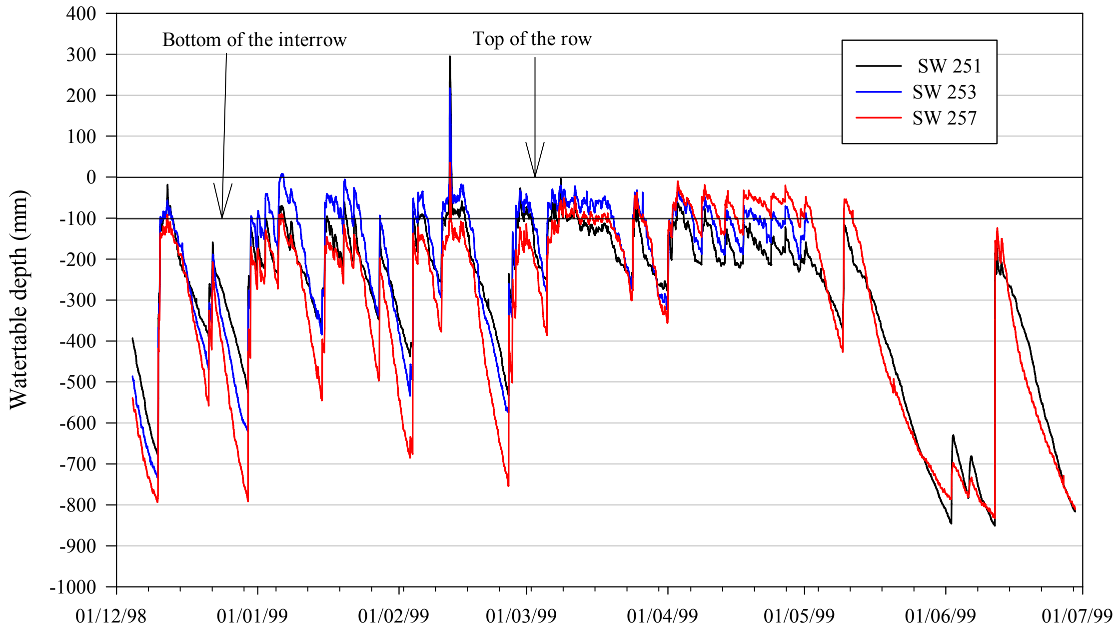
4.4.2.1 Palmas Site, 1998-99

The watertable depth at the Palmas Site was measured from December 1998 when three transects of three wells were installed in the field (Fig 4.2) until the above ground extensions wells were removed in July 1999 for harvest and re-installed in December 1999. When the wells were reactivated a shallow watertable was present. The second observation period ended in July 2000 and a shallow watertable was present for the whole of the observation period. The data presented in this section are all drawn from the middle transect located 250 m from the large field flume at the Palmas Site. The data from the two other transects are presented in the Appendix 2A (Figs A2.2-3).

The watertable hydrograph (Fig. 4.8) shows the watertable depth relative to the soil surface at the individual measurement locations. The watertable hydrograph is presented this way, as this is how the plant experiences the shallow watertable and waterlogging.

The watertable reacted very quickly to rain between December 1998 and July 1999 rising quickly on numerous occasions as the soil profile became saturated and the watertable intercepted the soil surface (Fig 4.8). Figure 4.8 shows the hydrograph of the watertable response with the height datum set at the top of the rows as the shallow wells were elevated approximately 100 mm above the interrow. The watertable frequently rose above the interrow to cause inundation, however only on 5 occasions did the watertable rise above the row at this position in the field. The large spike in the height of the watertable on 12 February 1999 was due to an extensive flood of the Herbert River. The logger in the middle shallow well (SW 253) failed in May 1999 and no further data were recorded.

(a) Watertable response



(b) Rainfall

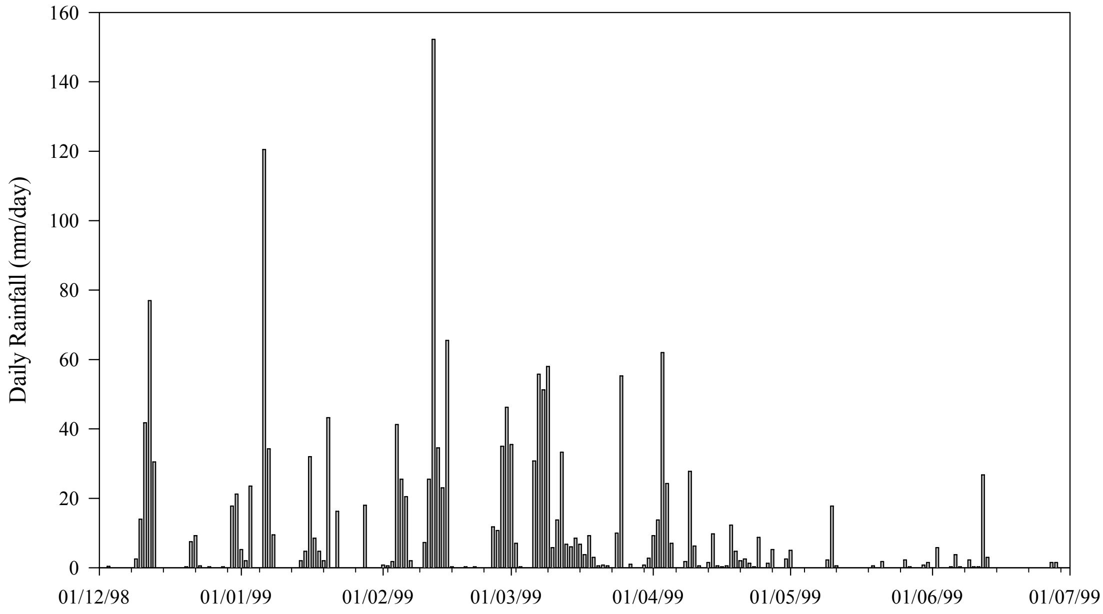


Figure 4.8 Watertable dynamics at the Palmas Site 1998-99: (a) Watertable depth fluctuations (legend refers to the middle transect of shallow wells located 250 m from main field flume (Fig 4.2)); (b) Daily rainfall measured at the Palmas site

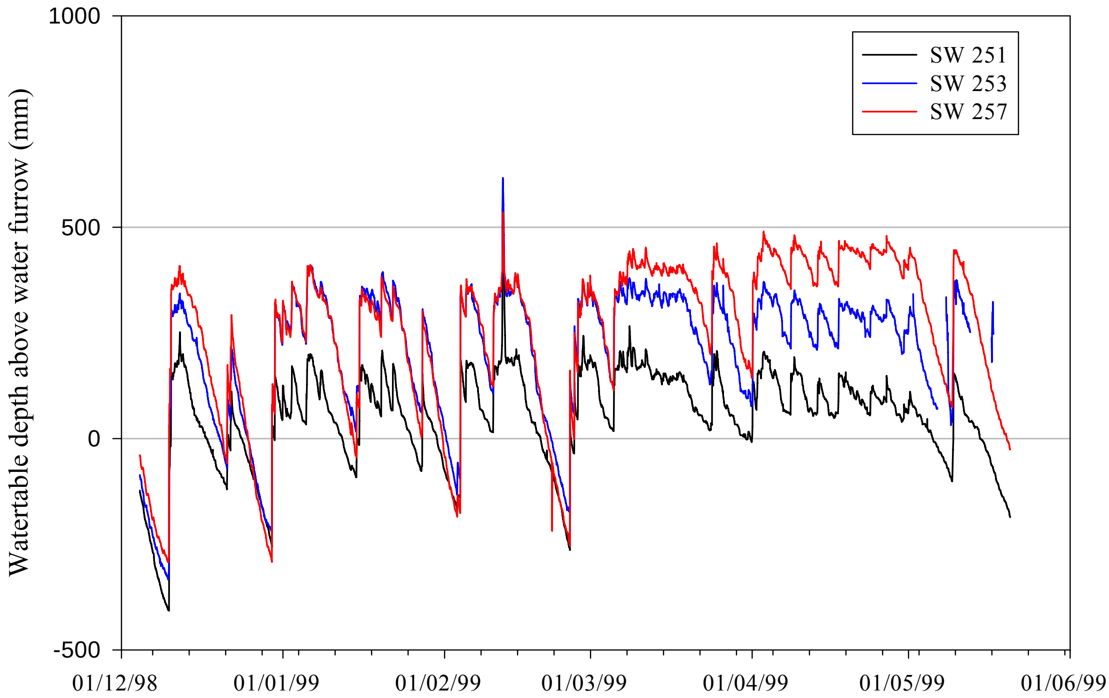


Figure 4.9 Watertable depth measured with respect to the water furrow in the middle shallow well transect at the Palmas site between December 1998 and July 1999 (SW 251 in row 1 SW 253 in row 3 and SW257 in row 7 away from the water furrow.

The watertable dropped slowly after rain but was always present throughout the 1998-99 wet season. The protracted duration of the shallow fluctuating watertables is well demonstrated in Figure 4.9 where for only 50 days, was the watertable below 0.5 m out of the 207 days of observation. The periods of inundation (Section 3.4.2.) were few compared to the extended period of waterlogging. The rapid dynamics of watertable fluctuations show that the watertable reacted by rising quickly, usually within the same hour as the rain fell (Fig 4.9). The watertable fell slowly when no rain fell, and on two occasions towards the end of the wet season the watertable fell continuously for more than 10 days (Fig 4.9).

A closer analysis of the difference between the watertable depths was undertaken by comparing the watertable depths measured at row 7 (SW 257 in Fig 4.9) to the watertable measured in row 1 (SW 251 in Fig 4.9) and 3 (SW 253 in Fig 4.9). The watertables plotted in Fig. 4.9 use the soil surface as the datum, however as noted in Section 3.3.1 there is a significant slope from row 7 to the bottom of the water furrow. This means that Fig 4.9 does not show the hydraulic gradient present from row 7 to the water furrow nor the shape of the watertable. To overcome this, the watertable depths were calculated with respect to the bottom of the water furrow to determine the shape of the watertable (Fig 4.9).

The evidence presented in Section 1.2.8 suggests that the depth of the watertable below the soil surface is critical to the sugarcane plants response to waterlogging. To determine the shape of the watertable and measure the hydraulic gradient the watertable is shown with respect to the water furrow (Fig 4.9).

At the start of the observation period in December 1998, there was no great difference between the watertable depths, from row 7 to row 1 (Fig. 4.9). However, as the watertable dropped in the middle of December 1998, the differences in depth became apparent, with the watertable in the row 7 (SW 257 Fig 4.9) much shallower than the watertable in row 1 (SW251 Fig 4.9). There was little difference between the watertables measured at row 7 and row 3 (SW 257 - SW 253 in Fig. 4.9) from the start of the observation period until the beginning of March 1999. From this time on the depth of the watertable mimicked the cross section of the field. The watertable became shallower with increasing distance from the water furrow (Fig 4.9).

The watertable measured in the middle at row 7 (SW 257) was deeper than the watertable measured at row 1 (SW 251) and the same depth as the watertable measured in row 3 (SW 253) until March 1999 (Fig 4.9). The difference in watertable depth between SW 257 and SW

251 occurred after the first rain event in December 1998. After this event the watertable was shallower at SW 257 throughout the season.

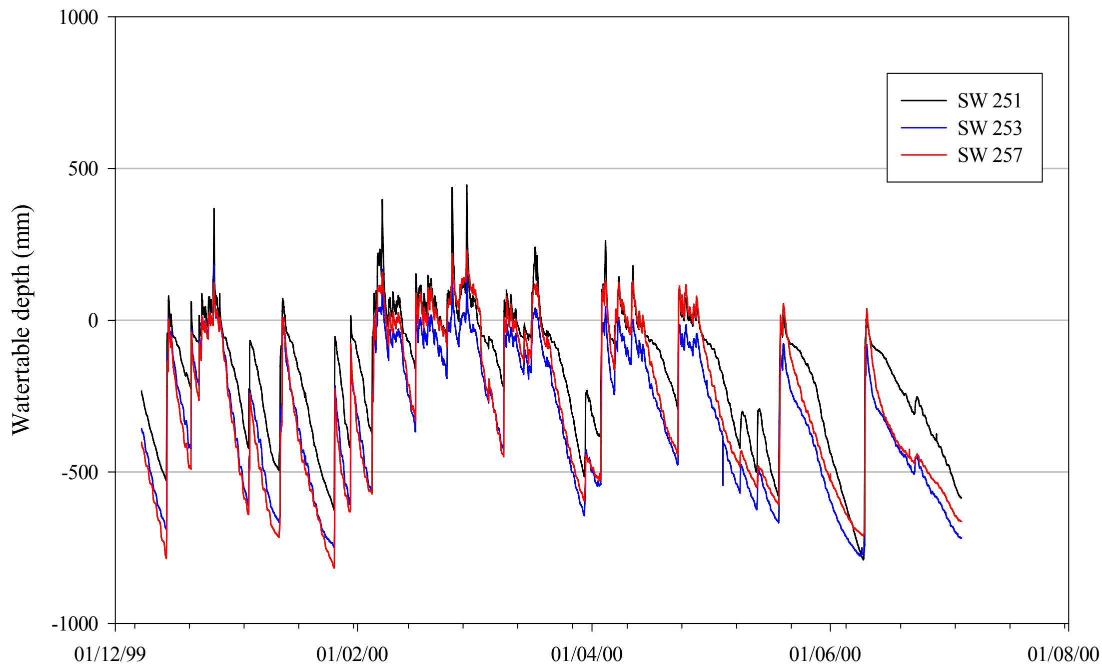
After March 1999 the difference between all the watertable depths increased, until the watertable measured in row 7 in May 1999 was 350 mm shallower than the watertable measured in row 1 (Fig 4.9). This difference in depth may be due to the inability of the water furrow to drain the field at a rate sufficient to match the rainfall rate. The result is a watertable much higher in the middle of the field between the two water furrows. This would have created a positive pressure gradient from row 7 to the water furrow that was maintained until the end of the observation period.

4.4.2.2 Palmas Site 1999-2000

The Palmas Site remained waterlogged for nearly all of the 1999-2000 wet season. The watertable again responded very quickly to rainfall with rapid rises after the onset of rain then a slow decline as the water was extracted for plant use or was lost as drainage (Fig. 4.10). The extent of the waterlogging at the Palmas site became clear as the watertable persisted for the duration of the 1999-2000 wet season. Overall, the watertable lay at depths shallower than 0.5 m for 637 days out of the 763 days of monitoring.

Four regional floods during the 1999-2000 wet season are shown by the peaks in the watertable depth of about 450 mm above the soil surface (Fig 4.10). More localized flooding occurred with smaller peaks towards the end of the measurement period causing floods of about 250 mm above the soil surface.

(a) Watertable response



(b) Daily Rainfall

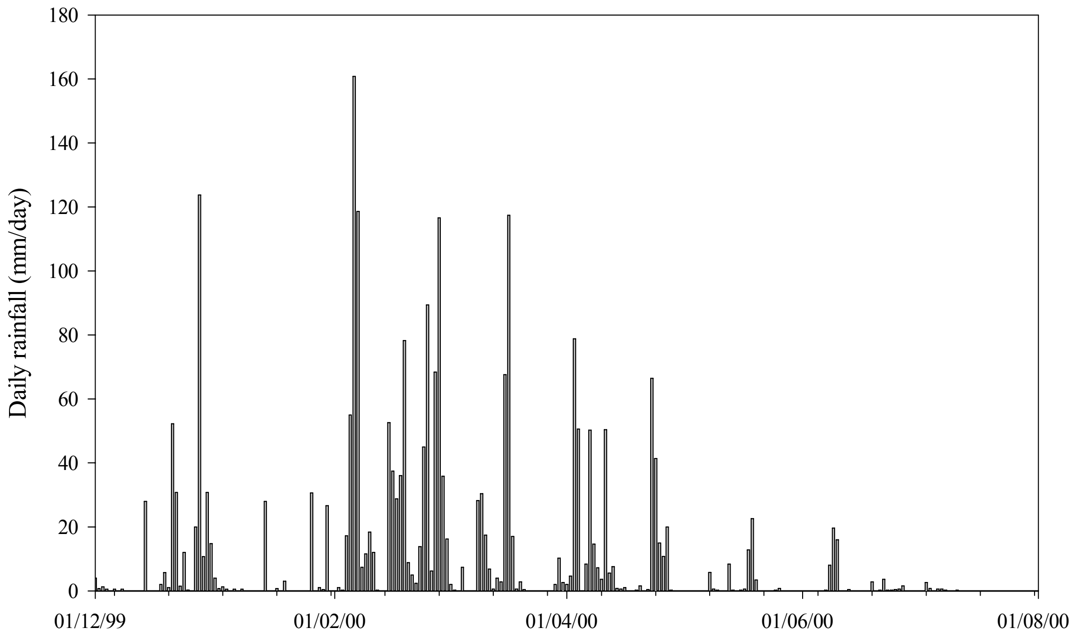


Figure 4.10 Watertable dynamics at the Palmas Site 1999-2000: (a) Watertable depth fluctuations (legend refers to the middle transect of shallow wells located 250 m from main field flume (Fig 4.5)); (b) Daily rainfall measured at the Palmas site

At the beginning of the measurement period, December 1999, the watertable depths were similar with respect to the water furrow in all the three shallow wells (Fig 4.11). The watertable response measured in SW 257 was also similar to that of the previous season, the watertable became shallower as the season progressed compared to the other two wells (Fig 4.11). Unlike the previous season, this difference in depth did not become manifest until February 2000, well after the first rain event. The greatest difference between the measured watertables appeared when the watertables were at the greatest depths, similar to the first half of the previous years observation season. Unlike the previous season however, there was no reversal of the trend and the watertable depth with distance from the water furrow and the watertable measured in SW257 was deeper than SW 251 for nearly all the second observation period.

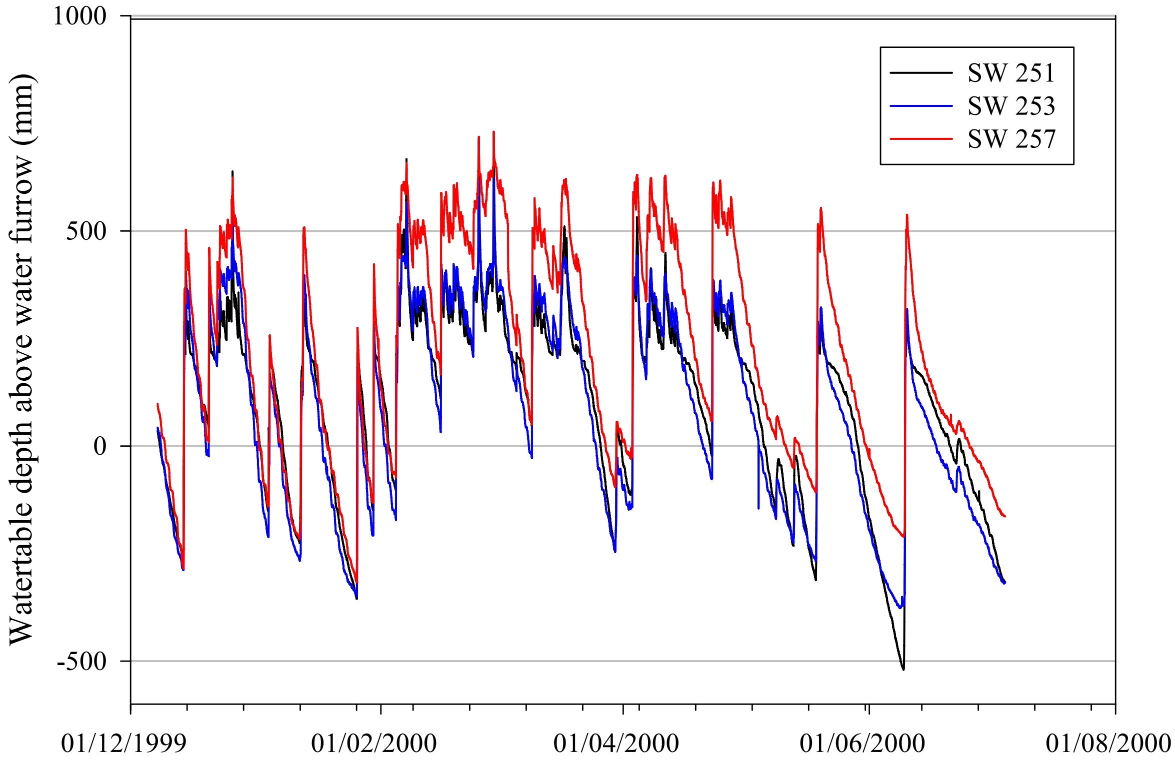


Figure 4.11 Watertable depth measured with respect to the water furrow in the middle shallow well transect at the Palmas site between December 1999 and July 2000

4.4.2.3 Lasered Palmas site

The shallow well located at the lower end of the laser-leveled field was 350 mm deep, and periodically dried out. This is represented by the flat watertable response at 350 mm depth of well LBP shown in Fig. 4.12. The shallow well located at the upper end of the field (LTP) measured very similar watertable fluctuation patterns (Fig 4.12). As at the Palmas Site, the watertable responded quickly to rainfall and declined slowly when the rainfall ceased.

The watertable dynamics of the perched watertable within field without water furrows (Lasered Palmas Site) matched the dynamics of the watertable at the neighbouring Palmas Site (Fig 4.13). The movements of the watertable appeared to be independent of the water furrows that were present at the Palmas Site. The water furrows had been assumed to drain the shallow watertable.

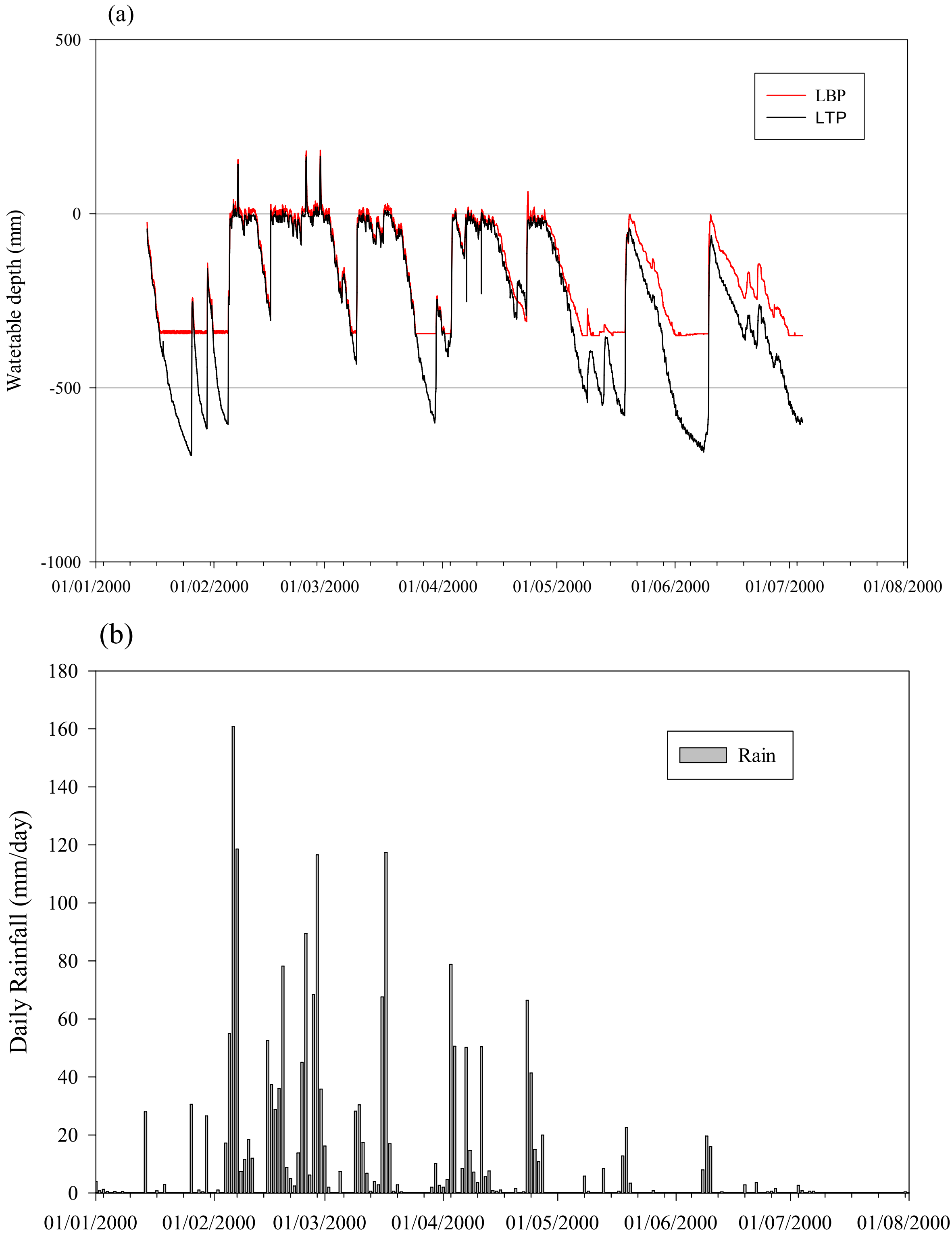


Figure 4.12 Watertable dynamics at the Lasered Palmas Site 1999-2000: (a) Watertable depth fluctuations (legend refers to the shallow wells located at the top of the field (LTP) and bottom of the field (LBP) (Fig 4.5)); (b) Daily rainfall measured at the Palmas site

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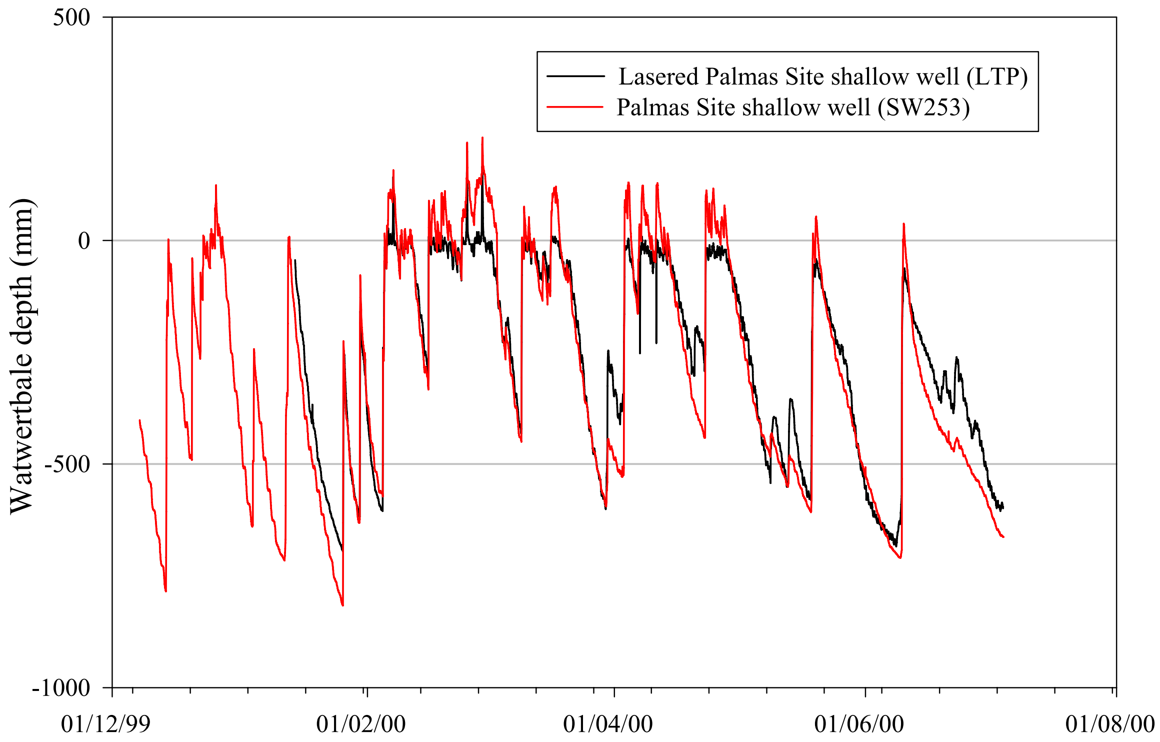


Figure 4.13 Comparison of watertable response between Lasered Palmas Site (black line) and Palmas Site (red line) respectively. The black line is the hydrograph from LTP, while the red line is the hydrograph from SW 253

4.4.2.4 Macknade Site

The watertable at the Macknade Site was observed from 16 December 1998 to 15 September 1999 and again from 26 October 1999 to July 2000. The watertable showed similar dynamics to those of the Palmas Site, rising quickly after rain and then slowly declining (Fig 4.14).

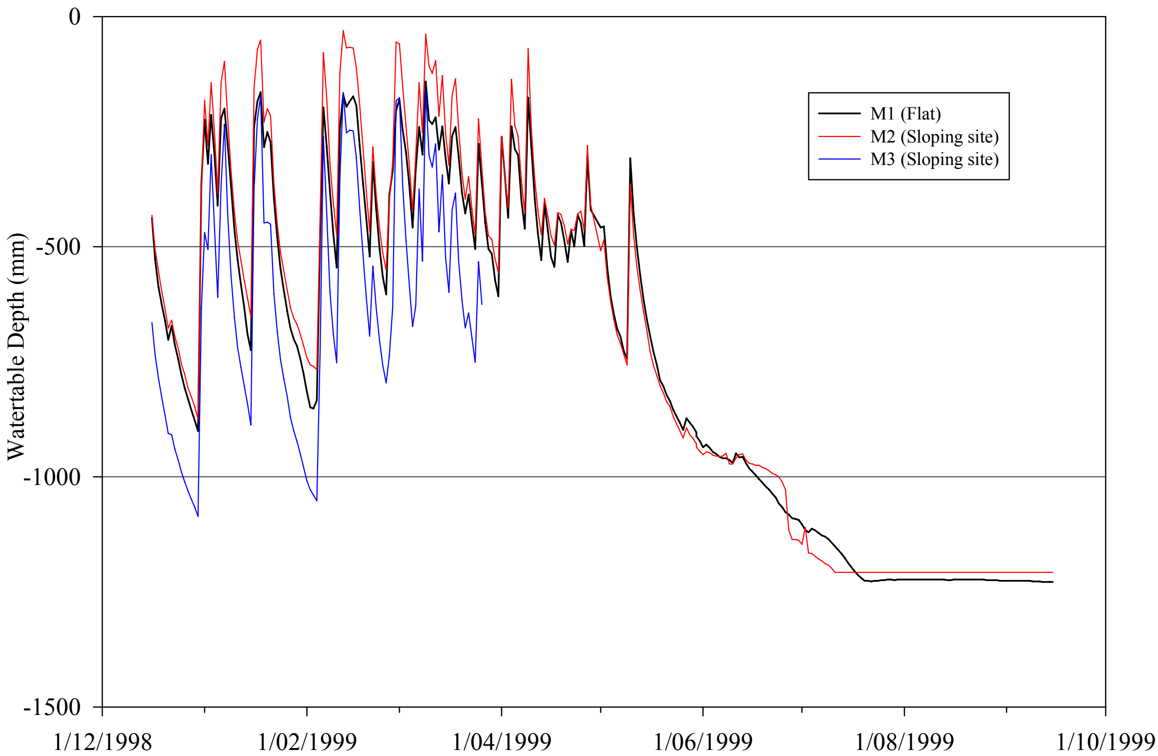


Figure 4.14 Watertable responses at Macknade Site during 1998-99 wet season

The watertable remained below the soil surface for all of the observation period (Fig. 4.14). When rain did not occur the watertable fell slowly but did not dry out or drop below the shallow wells until July 1999. The shallow well M1 was located in the flat plot and M2 and M3 were located in the plots with a slope of 0.0008 m/m. There does not appear to be any effect of the slope of the plot and the watertable response. The logger in the shallow well M3 failed in April 1999 and was not replaced until the following wet season.

The Macknade Site was situated well away from the regional drainage and was not affected by the flood that occurred on 12 February 1999.

4.4.2.5 Interflow

The drainage flux or interflow for the Palmas Site was calculated from Equation 4.4 and the results are presented in Table 4.8. The measured watertable depths were substituted into equation as the term H_m, the saturated soil hydraulic conductivity (K) determined in Section 4.4.1 was used, and the half drain spacing of 10.8 m was used to calculate interflow. A concurrent study (Bohl *et al.* 2000) calculated a water balance for the watertable at the Palmas Site and had measured deep drainage. Those figures are also included in Table 4.8.

Table 4.8 Components of the watertable water balance and percentage of the total water balance at the Palmas site for the three years of the study (1997-2000).

Year	Interflow (mm)	Evapotranspiration (mm)	Deep Drainage (mm)*	Total (mm)
97-98	213 (16%)	756 (58%)	332 (26%)	1301 (100%)
98-99	241 (19%)	683 (52%)	530 (14%)	1454 (100%)
99-00	165 (13%)	866 (67%)	220 (28%)	1225 (100%)
Average	206 (16%)	768 (59%)	361 (28%)	1335 (100%)

* from Bohl *et al.* 2000

Interflow was highly dependent on the height of the watertable above the base of the water furrow, as this governed the hydraulic head or driving force of the flux. Consequently, the amount of interflow varied with watertable depth (Fig 4.16) and for most of the observation period there was a constant flux of 0.1 mm/hr of interflow to the water furrows. In May–July 1998 the watertable fell below 0.4 m and interflow stopped. A high peak of interflow was calculated for 12 February (Fig. 4.15) during an extensive flood of the Herbert River; but this measure of interflow is unrealistic as floodwaters had inundated the fields, filled the drains and had created backwatering conditions.

The water balance for the watertable shows the dominant pathways of water leaving the watertable (Table 4.8). It was assumed that all of the water infiltrating into the soil entered the watertable. Interflow on average removed 16% of the water from the watertable over the three studied periods (Table 4.8). Evapotranspiration was by far the largest component of the water balance with an average 768 mm, or 59% of the total water that infiltrated the soil leaving by this pathway.

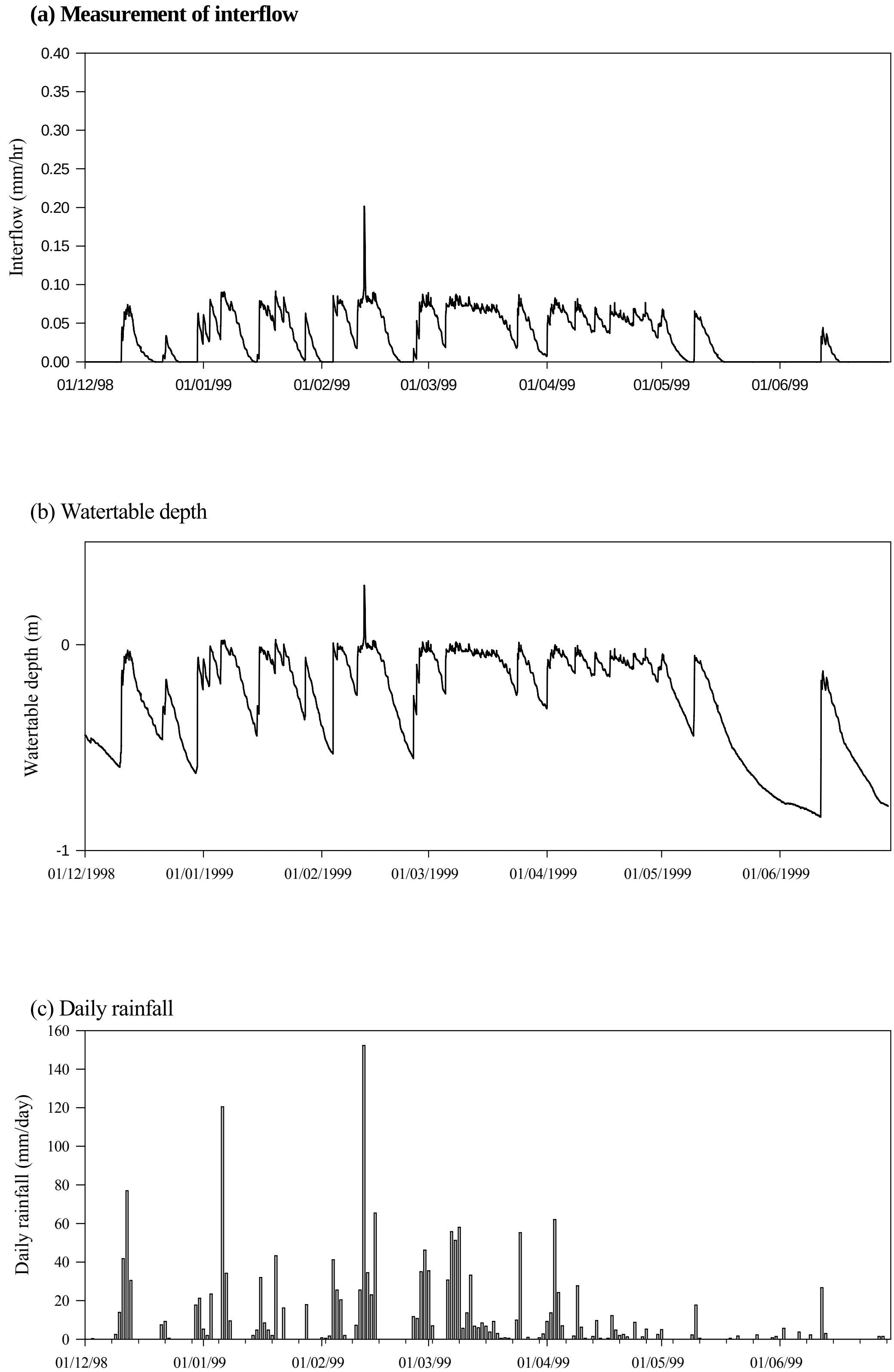


Figure 4.15 Interflow from the Palmas Site during 1998-99 wet season: (a) measured interflow, (b) watertable depth, (c) daily rainfall.

4.4.3 Water balance

A water balance was constructed by a combination of the measured deep drainage (Bohl *et al.* 2000), the volume of surface runoff determined in section 3.4.3, the measured interflow (Section 4.4.2.5), rainfall and evapotranspiration (Section 5.3). The water balance equation is

$$R = IF + ET + DD + RO \qquad \text{Equation 4.15}$$

Where
R is rainfall (mm)
IF is interflow (mm)
ET is evapotranspiration (mm)
DD is deep drainage (mm)
RO is runoff (mm)

Table 4.9 Water balance for the Palmas site (components shown as estimated values and as % of annual rainfall)

Year	Rain (mm)	Interflow (mm)	Evapotranspiration (mm)	Deep Drainage (mm)*	Runoff (mm)	Total
97-98	2596	213	756	332	982#	2283
	(100%)	(8%)	(29%)	(13%)	(38%)	(88%)
98-99	2153	241	683	530	853#	2307
	(100%)	(12%)	(32%)	(25%)	(39%)	(107%)
99-00	3018	165	866	220	1900	3151
	(100%)	(5%)	(29%)	(7%)	(63%)	(104%)
Average	2589	206	768	361	1245	2580
	(100%)	(8%)	(30%)	(14%)	(48%)	(100%)

* from (Bohl *et al.* 2000) # calculated from rating curve

The measured water balance shows that the direct runoff from rainfall events and evapotranspiration by the plant were the main sinks in the water balance (Table 4.9). In the 1999-2000 year over 60% of the rainfall ran off the field (Table 4.9). This was due to the high volume and intensity of rain that fell in that year (Section 3.4.3) with four large floods contributing to the high proportion of runoff (Section 3.4.2).

The evapotranspiration components of the water balance estimated over the three observation periods between 1998 and 2000 were similar, and were at the lower end of the range of 2-3 mm per day (Doorenbos and Kasam 1978); this reflected the waterlogged conditions experienced by the sugarcane for most of the three year period.

Deep drainage from the shallow watertable was a major component in the water balance, except in the final year when only 7% of the water left the field by this pathway; the highest proportion was 25% in the 1998-99 period (Table 4.9). The high percentage of recharge was due to the pattern of rainfall; there was persistent rain and a shallow watertable present for the whole of the observation period. It was assumed that due to the presence of the shallow watertable during this period there was a constant flux of water through the slowly permeable C horizon.

Interflow was not considered to be a significant part of the runoff component of the water balance at the Palmas Site (5-12%; Table 4.9), although interflow did exit through the flume, it was assumed that the flows were not measured as the flume was not sensitive to such low flows.

4.4.4 Measured crop yield

The sugarcane yield for the Main Palmas site in 1997-98 of 86 t/ha (Table 4.10) was close to the long-term Macknade Mill average of 90 t/ha (Briody 1998) and was higher than the 1997-98 mill average yield of 78 t/ha. The mill average yield for 1998-99 was lower than the long term average and was possibly a result of high rainfall experienced between late December 1997 and early January 1998. The higher sugarcane yield from the Palmas Site was possibly due to the watertable being below 0.5 m between late January and February 1998 (Bohl *et al.* 2000).

Table 4.10 Main site sugarcane yield 1998-99-00

Year	Cane yield (t/ha)			Macknade Mill average (t/ha)	Annual rainfall (mm)
	Main Palmas Site	Lasered Palmas Site	Macknade Site		
1997-98	86	Not measured	110	78	2596
1998-99	44	Fallow	90	69	2153
1999-00	68	54	85	48	3018

The 1998-99 sugarcane yield from the Palmas site was also well below the long term mill average and lower than the 1999 mill average of 69 t/ha (Table 4.10). This relates to persistent rain through the growing period and was one of the worst yields ever recorded on the farm (T. Palmas, pers. comm.). A detailed yield analysis of the Main Palmas Site revealed high variability in the sugarcane yield components within the field (Table 4.11). The sugarcane yields in the rows closer to the water furrow were much lower than the yields in the middle of the bed (Table 4.11). The yield components of the crop reveal that the possible main cause of the variability was lower numbers of stalks per m^2 (stalk density) the closer the cane grew to the water furrow (Table 4.10). There were no significant differences between the stalk densities so the variation in yield was not caused by this yield component.

Table 4.11 Yield components of the 1998-99 harvest at the Main Palams Site. Row is numbered in respect to distance from the water furrow

Distance from bottom of field (m)	Row	No. of stalks (/10m of row)	Stalk fresh wt (kg)	Weight /stalk (kg)	Number of stalks (/m^2)	Sugarcane Yield (t/ha)
100	1	85	No sample	No sample	5.7	39
100	3	99	No sample	No sample	6.6	40
100	7	109	No sample	No sample	7.3	58
250	1	75	60	0.80	5.0	34
250	3	105	89	0.85	7.0	41
250	7	123	196	1.59	8.2	67
350	1	79	No sample	No sample	5.3	34
350	3	86	No sample	No sample	5.7	42
350	7	92	No sample	No sample	6.1	67
Average						44

Crop yields for 1999-2000 period were also below average mainly due to persistent high rainfall through the growing season and rat damage (Table 4.10). The early growth of the cane appeared to be affected by record rainfall in November 1999 when over 600 mm of rain fell in the month. Sugarcane has been reported to be susceptible to excess water early in its growth cycle (Gayle *et. al* 1987) and the crop appeared never to fully recover from this set back. This was particularly the case of the sugarcane grown on the Lasered Palmas Site which was planted in late September and appeared to suffer reduced yield from the record high rainfall in November. Persistent rain from then, combined with another record rainfall for February, made this a very difficult season to grow sugarcane.

4.5 DISCUSSION

4.5.1 Soil hydraulic properties

4.5.1.1 Retention function

The measured soil moisture potential was fitted to the modified Van Genutchen soil moisture retention functions for both the A and B horizons. The measured data fitted the function reasonably well, with the main differences arising from the range of soil moisture in the A horizon (0.395 m^3/m^3 to 0.1 m^3/m^3) and in the B horizon (0.34 m^3/m^3 to 0.18 m^3/m^3). This difference in soil moisture retention is most likely due to the differences in soil texture and structure. There is differences in available soil water between the two horizons, with the A horizon having 0.295 m^3/m^3 as compared to 0.16 m^3/m^3 for the B horizon. The A horizon is a silty clay loam (Table 2.2) and this texture tends to release moisture more freely at the drier end of the soil moisture retention curve than the B horizon with a medium clay texture (Hillel 1998). The A horizon had many biopores and was well aggregated; the abundance of larger pores means that the soil could retain more soil water at higher soil moisture potentials than the less structured B horizon at a similar soil water potential.

4.5.1.2 Hydraulic conductivity

There were very noticeable differences in the hydraulic conductivities between the A horizon and the B horizon, as well as between the compacted soil of the interrow and the well structured soil of the sugarcane row. The interrow soil had become compacted due to the farming operations such as harvesting, fertilizing, and spraying. The observed well structured row (Table 2.2) had been undisturbed and the soil had displayed many aggregates and biopores and this may allow for rapid infiltration and high hydraulic conductivity. The medium clay B horizon is sub angular to blocky in structure (Section 2.1.5) and had few biopores, which in turn lowered the saturated hydraulic conductivity.

The saturated hydraulic conductivity of the soil varied greatly within the row and interrow soils as well as between soil horizons. However the four methods used to determine the hydraulic conductivity all produced comparable values (Table 4.6).

4.5.1.3 Specific yield

The specific yield (109 mm/mm) of the drained layer, consisting of the A and B horizons, was much lower than the figure quoted by Youngs (*et al.* 1989) of 0.27 mm/m. The difference between the values may be due to the heavier texture and the poor structure of the soil in the present study.

4.5.2 Watertable dynamics

The Palmas site was waterlogged, as defined by Rudd and Chardon (1977), for most of the study period as a result of a slowly permeable C horizon located about 1.0 m deep (Table 4.6). The watertable was very dynamic with rapid rises after rainfall followed by a slow decline. As water was removed from the watertable by evapotranspiration, deep drainage, and interflow, the watertable declined. The dominant process that caused this decline was evapotranspiration (Table 4.9). The determination of evapotranspiration is discussed below, in Chapter 5.

The watertable at the Palmas Site responded very rapidly to rainfall and Figures 4.10-12 show that the watertable began to rise after the onset of rain. After rainfall stopped, the watertable fell slowly as water drained to the water furrow as interflow, to the lower soil profile layers as deep drainage and was taken up by the plant through evapotranspiration. This pattern of rapid rise and gradual fall is shown for different sites in Figures 4.9-11, 4.13-15.

A perched watertable was present at the Palmas Site and either evapotranspiration or deep drainage could have driven the dynamics of the watertable. At a secondary site (Macknade Site) the pattern of rapid rise after rain followed by a slow decline was similar to that of the Palmas Site.

4.5.3 Water balance

The water balance for the field showed that the majority of rain left the field as surface runoff (Table 4.9). The processes and causes of runoff have been discussed above, in Section 3.4.2.

4.5.3.1 Interflow

Water drained from the watertable to the shallow open drains (water furrows) as interflow, however the amount of interflow was small (Table 4.9). A comparison between the watertable responses of a field without water furrows (Lasered Palmas Site) and a field with water furrows (Palmas Site) indicates that water furrows may not drain water from the watertable in high enough quantities to affect the level of the watertable (Fig 4.13). The presence of water furrows did not reduce the incidence of waterlogging on the poorly drained soils present at the Palmas Site compared with the Lasered Palmas Site without water furrows (Fig. 4.13). The amount of interflow was only a small component of the water balance (Table 4.9). The soil water drained to the water furrows from the watertable did not significantly reduce the duration or effect of waterlogging on the sugarcane.

4.5.3.2 Deep drainage

Deep drainage was a significant component of the water balance. More water left the field by deep drainage than interflow (Table 4.9) These data are from Bohl *et al*. (2000) and are replicated in the present study. Although the slowly permeable C horizon caused a perched watertable to develop, it still allowed a significant quantity of the water in the watertable to drain through it (Table 4.9). However the rate of deep drainage was not high enough to drain the watertable.

4.5.4 Crop yield

The sugarcane yield components of the 1998-99 crop revealed a strong declining trend across the field bed that was closely related to the depth of the watertable. The rows in the middle of the bed (row 7) had more stalks and were much heavier than the stalks closer to the water furrow in rows 1 and 3 (Table 4.11). This partly agrees with the observations of Deren and Raid (1997) who argued that decreased sugarcane yields from waterlogging were wholly attributed to decreased stalk numbers. However the present study also showed that stalk weights were also affected by waterlogging (Table 4.11). Deren and Raid (1997) found no significant difference between stalk weights of waterlogged and freely drained sugarcane.

4.6 CONCLUSIONS

Waterlogging of sugarcane in the heavy textured far levee soils of the Lower Herbert Valley, such as those at the Palmas Site, is caused by the low saturated hydraulic conductivity of the deeper soil horizons. The layers of low saturated hydraulic conductivity are located below 1 m depth and have saturated hydraulic conductivities of less than 0.8 mm/hr (Table 4.4). Combined with the low specific yield of the soil this means that 100 mm of rain is required to completely saturate the uppermost 1 m of soil.

Point measurements of watertable responses such as the individual shallow wells at the Palmas Site, provide good spatial representations of the watertable present in the field (Section 4.4.2.3). The nine shallow wells at the Palmas Site all showed similar watertable responses. The spatial and temporal patterns of the watertable dynamics were similar across the field (Fig 4.13). Comparison of the Palmas Site with water furrows, with the neighbouring Lasered Palmas Site, without water furrows and located 500 m away, showed a similar pattern of watertable fluctuation in both fields.

Sugarcane yields are affected by the presence of shallow watertables. Only in 1997-98 was the sugarcane yield of the three study sites close to the long term average yield. This was the only year that the sugarcane yield from the Palmas Site was higher than the district average; in the other years of the present study the yields at the Palmas Site were well below the district sugarcane yield average and well below the long-term district sugarcane yield average. The present study found that the lower yield was due to both decreased stalk numbers and stalk weights in response to waterlogging during the growing season.

CHAPTER 5 MODELLING PLANT AND WATER PROCESSES

5.1 INTRODUCTION

The hydrological processes that underlie surface drainage in low lying sugarcane fields including runoff, and the dynamics of the shallow watertables and interflow, have been estimated for the study sites in the Lower Herbert Valley in Chapters 3 and 4. In this chapter, the measurements of the processes and the measured sugarcane yields are used to calibrate computer simulation models that in turn are used to develop surface drainage criteria for low lying sugarcane fields (Chapter 6).

5.2 MODELLING APPROACH AND OBJCTIVES

The aim of the modelling in the present study is to accurately simulate the physical processes under varying climatic influences over a period of time. Specifically the aim of the runoff modelling is to accurately model the peak runoff rate and the length of time the field is inundated. These two parameters reflect the physical measurements required for development of inundation criteria. The peak runoff rate is required to optimise the shape; width and length, of the field the slope of the field, with the size of the field drain that will covey the runoff into the drainage systems. The time the runoff inundates the field is measured by the recession coefficient (τ) and again the model selected should accurately simulate these two parameters. The watertable model should accurately simulate the temporal dynamics of the watertable, specifically the sudden rise of the watertable after rain and the slow drawdown. Additionally the model should accurately determine when the shallow watertable is waterlogging the sugarcane that is when the watertable is within 0.5 m of the ground surface. The yield models should accurately predict the final yield of sugarcane exposed to waterlogging and excess water.

Many computer models are available that simulate individual physical processes (Hillel 1998). However few computer models are complex enough to fully simulate the interactions between runoff and watertable dynamics. No model could be found that replicates the biophysical reactions of sugarcane growing in soils subjected to excess rainfall. For these reasons a variety of models was used to simulate the different processes and the models were linked to understand better the interactions between the processes.

5.3 SELECTION OF MODELS

Various computer models that have been used to simulate runoff, watertable dynamics, interflow, and the yield of sugarcane subjected to excess water are reviewed below.

5.3.1 Runoff

Runoff from a heavy clay sugarcane field in Tanzania was measured and modelled by three empirically based models that simulated the runoff hydrograph (Smedema 1984). The models were a Linear Reaction model, a Travelling Time model, and the Soil Conservation Service Unit Hydrograph model (SCS UH). Each model was based on a different observed relationship (Smedema 1984). Other models including CREAMS (Haywood and Schulze 1990), ACRU (Haywood and Schulze 1990) and SWMM (Huber and Dickenson 1995) are also reviewed briefly in the following section.

5.3.1.1 Linear Reaction Model

The Linear Reaction Model (Smedema 1984) relates drainage discharge (q) at any time (t) to the dynamic storage (S_t) which is defined as not yet discharged rainfall stored on the soil surface.

It can be written as;

$q_t = \chi S_t$ Equation .5.1

where
q_t is the discharge (mm/hr)
χ is the reaction factor (per hr)
S_t is dynamic storage (mm)

$$\frac{dq}{dt} = \chi \frac{dS}{dt} = \chi(\mathrm{Re} - q)$$ Equation 5.2

where
Re is excess rainfall (mm/hr)

5.3.1.2 Travelling Time Model

The Travelling Time Model (Smedema 1984) relates the drainage discharge (q) to the time of concentration (t_c) for the basin when the storm duration (t) exceeds the time of concentration (t_c).

$q_t = \mathrm{CReA}_c$ Equation 5.3

where
C is the discharge coefficient
Re is the excess rainfall
A_c is the area of the total catchment
When t < tc then only part of the basin contributes to the discharge (Smedema 1984)

qt = CRe(A_t/ A_c) Equation.5.4

where
A_t is the contributing basin area at time t.

Inherent assumptions in the model are that discharge coefficient C, and the velocity of the discharge water remains constant during a runoff event.

5.3.1.3 Soil Conservation Service Unit Hydrograph

The Soil Conservation Service Unit Hydrograph transforms the excess rainfall into drainage discharge. Excess rainfall is derived from recorded rainfall by a curve number (CN) that represents the watershed cover/soil complex characteristics (Shirmohammadi *et al.* 1989).

The storm runoff is given (Shirmohammadi *et al.* 1989) as:

$$Q_s = \frac{(P_s - 0.2\Sigma)^2}{(P_s + 0.8\Sigma)}$$ Equation 5.5

Where
P>0.2S
Q_s is storm runoff (m)
P_s is storm rainfall (m)
Σ is the watershed retention parameter (m) represented by:

$$\Sigma = \frac{1000}{CN} - 10$$ Equation 5.6

Where
CN is the curve number with a range of 1-100

Smedema (1984) reported that he was surprised how well the linear reaction model described the runoff hydrograph, as the theory does not predict discharge to be related to dynamic storage. Smedema (1984) proposed that if the overland flow in the furrows was turbulent then the flow could be described by the Chézy channel formula;

$$q = \beta C_h \Gamma R^{\frac{1}{2}} S_b^{\frac{1}{2}}$$ Equation 5.7

Where
q is the discharge (m^3/s)
C_h is the Chézy Roughness coefficient (m/s)
Γ is the wetted cross section (m^2)
R is the hydraulic radius (m)
S_b is the bed slope (m/m)
β is the dimension factor (dimensionless)

Therefore according to equation 5.7 the discharge (q) is related to both the wetted cross section (Γ) and hydraulic radius ($R^{1/2}$) which are both, due to the channel geometry, dependent on the depth of water (d). As the depth of water increases so does the wetted cross section of the channel. The hydraulic radius is defined as the cross sectional area divided by the perimeter of the channel, for a wide open channel it is commonly taken as the depth of the flowing water (Hillel 1998). The results indicate that the relationship is nearly linear, for overland flow through small infield drains.

Using this relationship, Smedema (1984) calculated dynamic storage (S) for different water depths according to:

S_t=A/75 Equation 5.8

Where
S_t is dynamic storage (mm)
75 cm is the width of the base of the furrows
A is the area of the field (ha)

Smedema (1984) believed that the linear reaction model predicted the outflow well because of the fortuitous design of the field. This design was of mounded sugarcane approximately 250 mm high and the row spacing was approximately 750 mm apart. Smedema (1984) goes on to state that "the close fit of the linear reaction model does not really prove the validity of the of the underlying drainage flow conception". The other two models poorly described the outflow hydrograph.

5.3.1.4 Chemical Runoff and Erosion from Agricultural Management Systems (CREAMS)

CREAMS was initially developed by USDA-ARS and is a conceptual model which simulates peak runoff rate, total runoff, sediment yield, and plant nutrient and pesticide runoff from field-sized areas (Haywood and Schulze 1990). The hydrological component uses daily rainfall and monthly radiation and temperature data. Runoff is simulated two ways: CREAMS1 uses daily rainfall and Soil Conservation Service (SCS) curve number to predict runoff, and CREAMS2 uses the modified Green-Ampt infiltration model to estimate runoff volume (Haywood and Schulze 1990). CREAMS then uses the "cascading tipping bucket " approach to simulate the movement of water through the soil layers. When upper soil layer reaches field capacity then the model routes the soil water through to the next deeper layer.

5.3.1.5 Agricultural Catchment Research Unit (ACRU)

ACRU was developed by University of Natal as a distributed catchment model (Shulze 1998). It is a physically based model, which simulates storm flow and runoff as a function of soil water deficit, and uses a tipping bucket approach to distribute soil water through the soil profile (Shulze 1998). Stormflow is calculated by subtracting initial water abstraction such as depression storage, infiltration canopy interception and surface storage, from the subsequent rainfall intensity (Shulze 1998). Runoff is produced by a function of the magnitude of the rainfall and the soil water deficit from a critical response depth. The critical response depth has been found to depend mainly on the dominant runoff mechanism; saturated flow or Hortonian flow (Shulze 1998). The storm flow was divided into **quickflow**, water which flows out of the catchment on the same day as the event, and **stormflow** which is analogous to interflow. Evapotranspiration is estimated by atmospheric demand and the plant stage of growth. The model draws water from each soil layer, depending on the distribution and density of the roots (Shulze 1998).

Haywood and Shulze (1990) used the CREAMS and the ACRU models for runoff simulations. Runoff estimates were matched against those from four small agricultural catchments ranging in size from 2.7 ha to 6.6 ha, with slopes from 5% to 35%, and measured by weirs installed at the bottom of the individual catchments. Haywood and Shulze (1990) simulated an eleven year period during which runoff was recorded as monthly totals. Different cropping sequences were imposed which included growing sugarcane under a variety of soil conservation techniques such as strip cropping, terraces, and bare fallow.

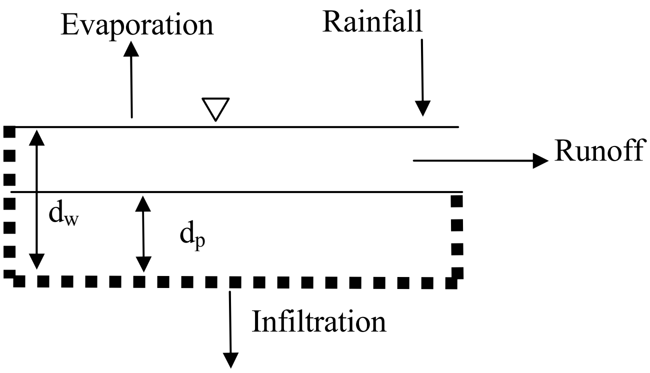
The researchers found that the CREAMS over-predicted total runoff for all catchments during the fallow stage by as much as 100% in some cases; under sugarcane it still over-predicted but the deviations were less. ACRU over-predicted runoff but not to the same extent as CREAMS.

5.3.1.6 Storm Water Management Model (SWMM)

Cameron McNamara (1984) used Storm Water Management Model (SWMM) (Huber and Dickenson 1995) to develop relationships of run off from sugarcane fields under varying rainfall conditions in the Lower Herbert Valley.

SWMM was developed by the United States Environmental Protection Agency to help design urban storm water systems (Huber and Dickenson 1995). SWMM is divided into 4 blocks. The runoff block uses the spatially lumped continuity equation coupled to the Manning's equation (Huber and Dickenson 1995) to simulate runoff. The model allows two surfaces to be present, one an impervious surface that does not allow infiltration and the other, a permeable surface that does. Using the permeable surface the model simulates infiltration by solving the modified Green-Ampt soil moisture infiltration equation (Huber and Dickenson 1995).

The runoff block solves the spatially lumped continuity equation by assuming the field can be represented as a reservoir. The reservoir has the depth of the water (d_w), and the detention storage (d_p), the amount of water that cannot runoff due to the micro topography of the surface.



Where
d_w is depth of water
d_p is depression storage
∇ is the water surface
Figure 5.1 Cross sectional diagram of how SWMM represents runoff from a field

The continuity equation is given by (Huber and Dickenson 1995):

$$\frac{dV_1}{dt} = A_f \frac{dd_w}{dt} = Ai^* = Q \qquad \text{Equation 5.9}$$

where
V_1 is the volume of water (A x d) (m^3)
A is wetted area (m^2)
d_w is depth of water (m)
t time (hr)
A_f is the area of the field (m^2)
i* is the rainfall excess (m)
Q is discharge (m^3/s)

The Manning's equation (Equation 3.5, Section 3.2.4) has been written by (Huber and Dickenson 1995) as:

$$Q = W_f \frac{(d_w - d_p)^{\frac{5}{3}}}{n} S_f^{\frac{1}{2}} \qquad \text{Equation 5.10}$$

Where
W_f is the width of the field
n is the Manning's roughness coefficient
S_f is the slope of the field
Combining equations 5.9 and 5.10 produces:

$$\left.\begin{aligned} Q\frac{dd}{dt} &= i^* - W_f \frac{(d_w - d_p)^{\frac{5}{3}}}{An} S_f^{\frac{1}{2}} \\ Q\frac{dd}{dt} &= i^* + \frac{W_f S^{\frac{1}{2}}}{An}(d_w - d_p)^{\frac{5}{3}} \end{aligned}\right\}$$ Equation 5.11

Equation 5.11 can be solved at each time step in a simulation of discharge of surface water by a finite difference scheme. The assumption that the Manning's equation is valid for the type of flow in the rows of a sugarcane field was examined in Section 3.3.

5.3.1.7 Unit hydrograph

The unit hydrograph is a common hydrological technique to relate excess rainfall to runoff (Pilgrim 1993). The unit hydrograph represents the effects of physical characteristics of the catchment on a completely defined, standardized input rainfall excess (Pilgrim 1993). Two assumptions underlie the unit hydrograph (Pilgrim 1993): the relationship between inflows into the catchment are proportional to outflows from the catchment; and that the input rainfall excess is uniform over the catchment.

The unit hydrograph ($U_{n-m+}1$) is defined as the watershed response to a unit depth of excess rainfall (P_m), uniformly distributed over the entire watershed and applied at a constant rate for a given period of time (Chow *et al.* 1988), such that:

$$Q_n = \sum_{m=1}^{n \le m} P_m U_{n-m+1}$$ Equation 5.12

Where`
Q_n is volume of direct runoff (m^3/s)
m is the number of pulses of rainfall

5.3.2 Watertable models

5.3.2.1 DRAINMOD

DRAINMOD is a computer model that simulates a water management system (Skaggs 1982) and calculates a water balance for a soil profile by simulation of the relevant hydrological processes. These processes are the rate of infiltration, drainage, evapotranspiration, and the distribution of soil moisture in the soil profile.

Precipitation is a major input into the model and assumes and the water that falls as rain is initially infiltrates into the soil. The model uses the infiltration function of Philip ((1954) cited in Skaggs 1982):

$$f_0 = \frac{a_p}{F} + B \qquad \text{Equation 5.13}$$

Where
f_0 is the infiltration rate of the soil (m/hr)
F is the cumulative infiltration (m)
a_p and B are parameters that depend on the soil properties (a_p m^2/hr, B m/hr).

Excess water that cannot infiltrate into the soil is initially stored as depression storage. The volume of depression storage is determined by two factors. A micro component consists of small depressions due to surface roughness, and the macro component is determined by larger surface depressions that can be altered by land shaping practices. When both components are filled, the model removes the additional water from the simulation as runoff.

The water that infiltrates the soil may cause the formation of a watertable. The groundwater is drained by drain tubes (subsurface drainage) or open ditches. DRAINMOD calculates the drainage rate by assuming the lateral movement of water to the drains is in the saturated zone of the soil profile. The model uses the horizontal saturated hydraulic conductivity in conjunction with the Hooghoudt steady state equation (Equation 4.2) (Bouwer and van Shilfergaarde 1963) to determine the flux to the drains.

DRAINMOD simulates the crop demand for water by calculating the daily potential evapotranspiration using the method developed by Thornwaite (1948). When the soil water limits the evapotranspiration rate, application of the method developed by Gardner (1958) is used by the model to determine the evapotranspiration rate.

5.3.2.2 APSIM Sugar

Agricultural production simulation model (APSIM; Keating *et al.* 1994) is a framework to simulate the production of sugarcane under different management scenarios. APSIM is a series of plug-in sub-models that simulate the soil water dynamics, the nitrogen balance, the growth of the plant and the interaction of the crop residue with the soil fertility. The water balance sub-model used in APSIM Sugar is SOILWAT, and the SUGAR (Robertson *et al.* 1994) is the sub-model used to simulate the growth of the plant.

SOILWAT is a cascading tipping bucket water balance with a daily time step based on CERES (Jones and Kinry 1986) and PERFECT (Littleboy *et al.* 1992). Water is distributed through the soil profile by saturated or unsaturated flow. When the soil moisture content of a layer is above the drained upper limit (DUL) of the soil, a fraction of the water drains to the next deeper layer each day. The saturated flow is described as:

$$\text{Flux} = \text{SWCON x (SW - DUL)} \qquad \text{Equation 5.14}$$

where
SWCON is the soil water conductivity (mm/day)
SW is the volumetric soil water content (mm^3/mm^3)
DUL is the drained upper limit of the soil in that layer (mm^3/mm^3)

When the soil water content is below the drained upper limit, the movement of the water depends on the water content of the adjacent soil layers and a function of the average water content of the adjacent layers. Runoff is calculated from the USDA-SCS curve number using the SCS unit hydrograph (Equation 5.5). Evaporation is assumed to take place in two stages, the first is air-limited evaporation and the second is soil-limited evaporation. The first stage evaporation assumes the soil is sufficiently wet for water to be transported to the surface at a rate at least equal to the potential evaporation rate. When the water content of the soil has decreased below a threshold value, the rate of the supply from the soil will be less than the potential evaporation. Potential evapotranspiration is calculated by the Priestly and Taylor (1972) method.

The sub-model SUGAR (Robertson *et al.* 1994) simulates plant growth by calculating canopy development by estimating the area of leaf. The area of leaf is calculated from the stalk number, leaf number per stalk, and individual leaf area. The crop dry weight accumulation is driven by the conversion of intercepted radiation via a radiation use efficiency term. The relationship between crop growth and crop water use is maintained by a transpiration efficiency (Robertson *et al.* 1994). While the plant available water term (PAW) and the potential fraction of available water term (kl) incorporate the effects of soil conductivity and root length density on the uptake of soil water (Robertson *et al.* 1994).

5.3.2.3 Youngs model

The Youngs *et al.* (1989) model was developed to simulate watertable dynamics in flat, low lying areas. The model requires three measured soil hydraulic properties: specific yield of the drained horizon, and the saturated hydraulic conductivities of the drained layer and the slowly permeable layer.

The model uses the concept of specific yield of an aquifer to relate flow, either to or from the watertable, to changes in height of the watertable. Specific yield is defined as the amount of water released or taken up by the unsaturated soil to the groundwater, with a unit height change in the watertable (Youngs et al. 1989).

The unsteady state of the watertable can be assumed to be a series of short term steady state positions. This assumption greatly simplifies the determination of the position of the watertable. Steady state analysis is useful when the design of the drainage system aims to keep the watertable at a known depth. By considering a series of steady state positions with small time increments, a pseudo-unsteady state can be replicated (Youngs *et al.* 1989).

The assumptions used by the model require the flux of water due to rainfall or evaporation to travel vertically to or from the watertable, and the fluxes from the watertable to the drain travel horizontally.

The model of Youngs *et al.* (1989) is represented as:

$$\Delta H = \left\{ \frac{(K_1 - K_o)}{A_m S D^2} \left[p\left(\overline{H_o} - b\right)^2 - j\left(\overline{H_{\max}} - b\right)^2 \right] + \frac{K_o}{A_m S D^2} \left(\overline{H_o}^{\alpha d} - i\left(i\overline{H_{\max}}\right)^{\alpha d} \right) - \frac{V_w}{S} \right\} \Delta t \quad \text{Equation 5.15}$$

Where
ΔH is change in watertable height (m)
Δt is the time increment between the steady states (h)
K_1 is hydraulic conductivity of the drained layer (m/hr)
K_0 is hydraulic conductivity of the slowly permeable layer (m/hr)
A_m is a dimensionless shape factor for the ditch layout and varies from between 0.5 for square to 0.911 for rectangular areas
S is the specific yield (m/m)
D is half the distance of the drain spacing (m)
H_0 is the water height in the drain (m)
H_{max} is the maximum watertable height at the mid point between the drains (m)
V_w is the flux to or from the watertable (positive up) over the time period (1hr) (mm)

d depth to impermeable layer (m)

α^d is a dimensionless factor dependant on d
where
$\alpha^d = 2(d/D)^{d/D}$, $0<d/D<0.35$, $\alpha^d = 1.36$, $0.35<d/D<\infty$
b is the depth to impermeable layer if the division between the drained layer and the impermeable layer is above the base of the ditch (m)
j=1 when $H_m>b$
j=0 when $H_m<b$
p=1 when $H_o>b$
p=0 when $H_o<b$
i=1 when $(H_o/D)^{\alpha} > V/K_1$
i=-1 when $(H_o/D)^{\alpha} < V/K_1$

The volume of water per hour that flows to the watertable as rainfall or was removed from the watertable by evapotranspiration is required as an input into the model, to solve the equation and determine the change in watertable height. To model continual change of the watertable height the initial watertable height, is required and is supplied from the data collected in the field (Section 4.4.2).

The Youngs model assumes that the drained layer has a uniform saturated hydraulic conductivity. In the present study this was not true, because there were two distinct saturated hydraulic conductivities for the A and B horizons (Table 4.16). Therefore the model was set up to use the different saturated hydraulic conductivities of the two soils horizons. The hydraulic conductivity value used in the model depends on the soil horizon in which the watertable was calculated at the previous time step.

The Dupiut-Forchheimer assumption of parallel streamlines (Section 4.2) may be invalid for close drain spacing in the Youngs model and may cause an error in the prediction of the shape of the water table. However, Cook and Rassam (2002) demonstrated that the Youngs model could be used to simulate drainage to shallow open drains on heavy soils. It should be noted that the Youngs model only approximates the complex dynamics that take place.

5.3.2.4 HYDRUS-2D

HYDRUS-2D (Simunek *et al.* 1999) is a finite element model for simulating movement of water, heat, and multiple solutes in variably saturated media. The program solves the Richards' equation for saturated/unsaturated water flow (Simunek, *et. al.* 1999). The model simulates two-dimensional water flow and the water flow equation incorporates a sink term to account for water uptake by plant roots. HYDRUS-2D allows incorporation of drains either as a seepage face or as tile drains. The potential seepage face must be identified before operating the model. At each iteration, HYDRUS-2D treats the saturated part of the potential seepage face as a prescribed pressure head boundary and the unsaturated part of the soil is treated as a prescribed flux boundary. The prescribed pressure head is solved using the technique set out in Neuman (1974). The prescribed flux boundary is solved by time-dependent ordinary differential equations with non-linear coefficients in a matrix form. HYDRUS-2D allows three types of soil moisture potential functions to describe the soil hydraulic properties, using van Genuchten (1980), Brooks and Corey (1966), or modified van Genuchten type equations (Vogel *et al.* 1988).

5.3.3 Yield models

The physical processes of water movement and the biological processes of plant growth need to be linked to optimize a surface drainage system, and to reduce the impact of the shallow watertable on the sugarcane yield. Little is known about the biological processes of sugarcane grown in excess water. Nevertheless there are two simple empirical models that link the decrease in potential biomass production of sugarcane with watertable fluctuations.

5.3.3.1 Gayle model

Hiler (1969) developed a stress index for crops and this was adapted to sugarcane by Gayle *et al.* (1987). These concept was used to relate stress caused by excessive soil water conditions to sugar cane yield. The **stress day index** (SDI) is a way of quantifying the cumulative stress imposed on a crop during the growing season. It can be expressed as

$$SDI = \sum_{i=1}^{\nu} CS_i \times SD_i \qquad \text{Equation 5.16}$$

Where
SDI is the stress day index
ν is the number of stages of crop growth (for sugarcane this is three)
CS_i is the crop susceptibility factor
SD_i is the stress day factor for the stage of plant growth or time period
Crop susceptibility was defined (Gayle *et al.* 1987) as:

$$CSi = \frac{Yo - Yi}{Yo} \qquad \text{Equation 5.17}$$

Where
Yo is the potential yield
Yi is the crop yield during growth stage i

From previous experiments (Gayle *et al.* 1987), a three-step stress day limit for sugarcane was used in the model (Gayle *et al.* 1987). The assumptions used by the model were that the critical water table depth at which stress occurs is 0.45 m (Section 1.2.8) and the only stress that affects the plant was excessive water. It was also assumed that evapotranspiration demands by the plant would be met at all times. Gayle *et al.* (1987) divided the growing season of the sugarcane into three stages and defined three crop stress factors (CS_i) (Table 5.1).

Table 5.1. Growth stages of sugarcane and crop stress factors (CS_i)

Growth stage	Days after planting	CS_I
1. Early growth	0-130	0.6

2. Grand growth	131-260	0.4
3. Maturity	261-291	0.01

The stress day factor in equation 5.17 is a measure of the cumulative stress during a given growth stage. Gayle *et al.* (1987) assumed that the stress was primarily due to excessive soil water conditions that are evident when the watertable was above 45 cm. This can be expressed as

$$SEW_{45} = \sum_{i=1}^{\mu} (45 - X_j)$$ Equation 5.18

where
SEW_{45} is the sum of excess water above 45 cm (cm)
X_j is the average depth from the soil surface to the watertable during each day (cm)
μ is the number of days in the growth stage (days). (Gayle et al. 1987)

Negative terms within the summation are neglected (Gayle *et al.* 1987).

Gayle *et al.* (1987) related the sum of excess water (SEW_{45}) via the stress day index (SDI) to the growing season such that:

$SDIW = SEW_{45} \times SDI$ Equation 5.19

where
SDIW is the is the stress day factor for the cane growing season

A relationship between yield and SDIW was then determined by correlating the relative yield to the SDIW such that (Gayle *et al.* 1987):

$$YR = 100 - .042 \; SDIW$$ Equation 5.20

where
Relative yield and is defined as

$$YR = \frac{Observed \quad yield}{Potential \quad yield}$$ Equation 5.21

where

YR is the relative yield
Observed yield is the yield measured at the site
Potential yield is the maximum observed yield for the site

Sugarcane can tolerate the stress induced by 3-5 days of waterlogging (Gayle *et al.* 1987). Five days of flooding during period I corresponds to a SDI = 5 x 45 x 0.6 which equals 135(Gayle *et al.* 1987). An additional regression analysis was carried out where YR is 100 and SDI 135, saturated conditions occurring for 5 days such that (Gayle *et al.* 1987):

$$YR = 106.5 - .048SDI \qquad \text{Equation 5.20}$$

5.3.3.2 Rudd and Chardon model

Rudd and Chardon (1977) developed a simple model that imposed a yield reduction for every day the watertable is above 0.5 m (Section 1.2.8). They assumed there was no waterlogging stress when the watertable was below 0.5 m. They also assumed that the waterlogging effect on yield is independent of the watertable height when the watertable was above 0.5 m, and that the watertable effect only occurs between December and June.

Rudd and Chardon (1977) derived two empirical relationships for the yield relationship between watertable depth and sugarcane yield decline:

- For shallow watertables depths (0-1.0 m): every 0.10 m lowering of the watertable increases sugarcane yields by 11.3 t/ha
- For every day the water table is shallower than 0.50 m, the sugarcane yield is reduced by 0.46 t/ha.

5.3.4 Model selection

5.3.4.1 Runoff model

The model used in the present study to simulate runoff should address the effect of slope, field dimensions, and hydraulic resistance on the discharge hydrograph. The model must be able to simulate how changes to the field design, such as field slope or field length will affect the discharge hydrograph.

From the material discussed in Section 5.3.1 above, the surface hydrological models can be divided into two groups: either analytical or physical models. Catchment responses to rainfall are implicit in analytical models, such as the ACRU, CREAMS, SCS unit hydrograph models, the catchment is considered spatially as a single entity and excess rainfall is transformed into a discharge hydrograph. Such an approach has been called a “black box approach” to modelling and understanding the relationships between individual processes are not required. On the other hand physical models, such as SWMM (section 5.3.1.6), aim to replicate the physical processes of the catchment response and require description of the catchment to simulate its response to rainfall.

One of the aims of this thesis is to understand how changes in field design can influence the discharge hydrograph, and a model that can simulate the interactions between the physical processes is required. SWMM (Huber and Dickenson 1995) was chosen as the surface water model as it could simulate the field dimensions and hydraulic resistance (section 5.3.1.6).

To test if the physical modelling would simulate the complex flow patterns described in Section 3.4.2, a unit hydrograph was developed for the field. The SWMM results were compared to the unit hydrograph to test the robustness of the physical model.

5.3.4.2 Watertable model

The use of a model that represents the physical processes of watertable fluctuations explicitly is more advantageous than a model that simulates a series of steady states watertables, but the benefits are offset by the effort required to parameterize such a model. Therefore to use a model that is based on soil physics and developed from land drainage theory provides the advantage of a physically based model but not constrained to lengthy parameterization and execution steps.

The model proposed by Youngs *et al.* (1989) was chosen as the watertable model mainly due to the ease of parameterisation and the simplifying assumptions used in the model (Section 5.3.2.3). The model requires only three measured soil parameters, hydraulic conductivities of the drained and impermeable layers as well as the specific yield of the drained layer. The assumption that unsteady watertable dynamics can be simulated by a series of steady state equations eases the computing power required. The Youngs model can be coded into a spreadsheet, while the other models require more sophisticated computer programming.

5.3.4.3 Yield Model

The effect of the watertable on the yield of sugarcane was modelled using both of the empirical models available, the Gayle *et al.* (1987) and Rudd and Chardon (1977) models. Both models were chosen due to the lack of detailed biological knowledge of the effect of excess water on the yield of sugarcane.

5.4 MODELLING METHODS

5.4.1 Statistical methods to assess model results

The aim of the modelling in the present study is to accurately simulate the physical processes under varying climatic influences over a period of time (Section 5.2.). Therefore it is necessary to use a number of statistical methods that quantitatively measure the goodness of fit between the modelled and measured results. This process has been referred to as critical evaluatory procedure (Addiscott *et al.* 1995) and involves testing the model against the range of measured results that has been collected under a wide range of climatic conditions.

The concept of goodness of fit is critical to this discussion; this term implies that by a model simulation match the measured results this provides an evaluation of the model's predictive ability (Legates and McCabe 1999). To test this ability of matching modelled results to measured results an difference or a measure of error is calculated. This measure of error is usually a relative measure between zero and one based around the coefficient of determination (r^2) (Legates and McCabe 1999). The coefficient of determination is the proportion of the total variance in the observed data that can be explained by the model ranging from zero, where the model explains none of the variance, to one where the model explains all of the variance (Steel and Torrie 1985).

This can lead to quite high values of r^2 due to the model simulating a large event well but numerous smaller not so well.
The coefficient of efficiency (E) (Equation 5.21) has been suggested as a superior method of evaluating models (Legates and McCabe 1999), as E is the ratio of the mean square error to the variance in the observed data subtracted from unity (Nash and Sutcliffe 1970).

$$E = 1.0 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(O_i - \overline{O}_i)^2} \qquad \text{Equation 5.21}$$

Where
O is observed data
P model simulated data

This means that if the value of E is zero or higher then the observed mean is a good a predictor as the model of the E is negative then the observed is a better predictor than the model (Wilcox *et al.* 1990). However this measure is still sensitive to extreme values (Legates and McCabe 1999).

To overcome the insensitivity of correlation based measurements to difference in observed and modelled simulated means and variance Willmot (1981) developed the index of agreement (d). Given by

$$d = 1.0 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(\left|P_i - \overline{O}\right|) + (O_i - \overline{O}_i)^2} \qquad \text{Equation 5.22}$$

This parameter d has a value between zero and one with the higher the value the better agreement (Willmot 1981). This parameter is the ratio of the means square error and the potential error subtracted from unity (Willmot (1981).

The usefulness of these two parameters E and d are demonstrated by the range of values generated by these statistics. E has a range of negative infinity to one, as discussed above the parameter needs to be equal or greater than zero to provide a measure that the model is simulating the process as well as the measured data. While d has a range of zero to one and can be similarly interpreted as the coefficient of determination (Legates and McCabe 1999).

5.4.2 Surface water modelling

5.4.2.1 SWMM

The data required for SWMM were the width, length and slope of the catchment, Manning's n, and the percentage of surface area that was impervious. The width, length, and slope for the main Palmas study site were measured, the Manning's n value was taken from the depth discharge determination in section 3.4. A fully impervious surface was assumed, and was supported by the determination of saturation overland flow (Section 3.4.5). This assumption was made on the grounds that saturation excess flow was the dominant flow regime present in the sugarcane field. When saturation excess flow occurred, all additional rainfall was assumed to be direct runoff. The assumption was incorporated into the model by setting the impervious area to 100%.

Hourly rainfall measured at the site was used as data input to the model but it became clear when studying the initial measurements that the watertable and surface flow reacted within minutes of initiation of rainfall. Therefore, rainfall data over 5 minute intervals were derived from the tipping bucket rain gauge located at the Palmas Site. The validation data for the model was from the small runoff events recorded between 15 and 19 February 2000 (Fig 3. 26)

Validation of the Mannings' n parameter used in the surface water model required accurately measuring the discharge from the Palmas Site, and this was only possible after the doppler velocity meter was installed into the large field flume in March 1999 (Section 3.4.2). Due to the extreme events in the 1999-2000 wet season, only a small part of the data set was available for calibrating the model. The period between 15 February and 19 February 2000 was again taken as calibration and validation was the single event measured on 3 April 1999 (Fig 3. 25).

The initial Manning's n value used for the model was the 0.3 which was the value derived from the run-on experiment presented in Section 3.4.1. The Manning's n was varied from 0.3 to 0.035 through a series of iterations, the simulated discharge hydrograph was compared to the measured discharge hydrograph. The optimum fit was determined by analysis by three statistical tests: the residual mean square error (RMSE); the coefficient of efficiency (E) and the index of agreement (d).

Runoff from the Lasered Palmas Site was modelled and compared with the measured data (Section 3.4.4.3). The surface model could not accurately simulate the measured low flow rates from the individual rows. To overcome this problem, the individual measured row data was scaled to simulate the response of one hectare of laser-leveled field and multiplying the measured single row discharge by 14. The measured data was compared to the modelled result from a 1 ha field.

5.4.2.2 Unit hydrograph

To derive a unit hydrograph for the Palmas Site, excess rainfall and runoff had to be estimated. Excess rainfall was calculated from the measured discharge data in the 1999-2000 wet season (Table 3.7). The calculated runoff coefficient in Table 3.18 is the ratio of discharge to rainfall and the average value for the 4 measured rainfall events of February 2000 was 73%, the value used for the excess rainfall calculation of the unit hydrograph. This loss modelling is commonly referred to as the runoff coefficient concept and is one of the basic assumptions underlying the widely used rational method (Maidment 1992). This is one of the simplest methods of transforming excess rainfall into streamflow however the unit hydrograph developed in the present study underpin a regional approach to modelling the drainage flow in the Ripple creek catchment (Post *et al.* 2003).

Initially the hourly excess rainfall was calculated for the 15 February 2000 runoff event by multiplying the hourly rainfall by 0.73. However the responsiveness of the field to rainfall (Fig 3. 26) was such that half hourly rainfall intervals were needed to capture the runoff process . The ordinates of the unit hydrograph were determined by the procedure of Maidment (1993).

5.4.3 Watertable models

The soil hydraulic parameters (Section 4.4.1), saturated hydraulic conductivity of the A, B, and C soil horizons, and specific yield were used as inputs into the Youngs *et al.* (1989) model of watertable-rainfall responses. These soil hydraulic parameters represent measured physical values and are not optimised values of parameters fitted to a measured watertable response. The model was applied over three years from September 1997 to August 2000 as this represented the period of watertable monitoring at the Main Palmas Site and also three complete crop cycles during the period of the present study.

The Youngs *et al.* (1989) model also required an atmospheric flux, either rainfall or evapotranspiration (ET_{crop}). An automatic weather station at the site collected temperature, relative humidity, wind run, solar radiation and rainfall on an hourly basis. Evapotranspiration was initially estimated in the first year (1997-98) by the APSIM Sugar model (Section 5.3.2).

The APSIM Sugar model required soil hydraulic parameters (Section 4.4), and climate data from the weather station at the Palmas Site. The model was run and the biomass yield of sugarcane was calculated and the modelled evapotranspiration (ET APSIM Sugar) was recorded. The model did not account for the effect of waterlogging on the yield of sugarcane. To overcome this, the measured 1998 sugarcane yield was divided by the APSIM Sugar model yield. This generated a ratio of 0.56 that was in turn used to scale the calculated evapotranspiration (ET APSIM Sugar) to ETcrop (G. Inman-Bamber, pers. comm.).

The Youngs model was then run using the ET_{crop} value outlined above and the measured watertable hydrograph was compared to the simulated watertable hydrograph. The index of efficiency (E) and the coefficient of determination (d; Legates and McCabe 1999) were calculated to determine the goodness of fit.

Table 5.2 Parameters used in Youngs *et al.* (1989) model and source of derivation.

Model parameter	Parameter name	Section where parameter is derived in this thesis	Value
$K_{1A\ Horizon}$	Hydraulic conductivity of the drained layer, (A horizon)	4.4.1	0.023 m/hr
$K_{1B\ Horizon}$	Hydraulic conductivity of the drained layer, (B horizon)	4.4.1	0.00085 m/hr
K_0	Hydraulic conductivity of the impermeable layer	4.4.1	0.0001 m/hr
A_m	Field shape factor	2.1.1	1.36
S	Specific yield of the drained layer	4.4.1	0.1
D	Half drain spacing	2.1.1	10.8 m
H_m	The maximum watertable height at the mid point between the drains	4.4.2	0.4 m

For the scenario analysis over the longer time periods, the evapotranspiration had to be calculated from historical records for input into the Youngs model. The determination of evapotranspiration using the measured yield to scale the evapotranspiration could not be done in years for which no yield data were available. To overcome this, the sum of the ET_{crop} between 16 September 1997 and the 16 September 1998 was divided by the sum of the potential evapotranspiration (ET_o) over the same time period. This calculated a whole season crop coefficient (Kc) of 0.65. The potential evapotranspiration (ET_o) was calculated by the Penman-Monteith equation (Smith 1998):

$$ETo = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T - 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \qquad \text{Equation 5.21}$$

where
ETo is the potential evapotranspiration (mm/d)
R_n is the net radiation (MJ/m^2/day)
G is the soil heat flux (MJ/m^2/day)
T is mean daily air temperature at 2 m (^{o}C)
U_2 is the wind speed at 2 m height (m/s)
λ is the latent heat of vaporization (MJ/kg)
e_s saturation vapour pressure (kPa)
e_a actual vapour pressure (kPa)
e_s - e_a saturation vapour pressure deficit
Δ represents the slope of the saturation vapour pressure-temperature relationship
γ is the psychrometric constant (kPa/°C)

The individual crop coefficients for the growth phase of sugarcane were calculated to reflect the different growth periods of the crop (Table 5.3). Doorenbos and Kassam (1979) derived ranges of crop coefficients to scale ET_o to ET_{crop} by splitting the crop cycle into five phases: initial, early, mid, late, and harvest; their crop coefficients were used initially in the present study to derive local crop coefficients. The values of the crop coefficients, calculated by manual changes to the values presented by Doorenbos and Kassam (1979), and the calculated ET values were then used as inputs into the Youngs model. The values were changed until the simulated 1997-98 watertable response by the Youngs model matched the measured watertable response.

ET_{crop}, required as an hourly input into the Young's model, was calculated daily and partitioned hourly by assuming that hourly ET_{crop} was determined by hourly solar radiation. The hourly solar radiation was used to distribute ET_{crop} over the day by calculating the percent of total daily radiation received in that hour.this figure was then used to calculate the ET_{crop} for that hour. The measured hourly rainfall data were also used in the model.

Table 5.3 Sugarcane crop coefficients for calculation of ET from Penman-Montieth equation.

Date (1997-98)	Growth phase	Range of Crop Coefficients (Doorenbos *et al.* 1979)	Calculated crop coefficient
16/9 to 14/11	Initial	0.4-0.5	0.4
15/11 to 31/11	Early	0.7-1.0	0.7
1/12/ to 31/1	Mid	1.0-1.3	0.8
1/2 to 31/5	Late	0.75-0.8	0.7
1/6 to 15/9	Harvest	0.5-0.6	0.4

5.4.4 Crop yield models

The watertable at the Palmas and Macknade Sites were not continuously monitored (July 1999-Nov 1999), so the gaps in the measured data were filled with the modelled watertable response. The sugarcane yield data used to verify the yield models were taken from Section 4.4.4.

The sugarcane yield models calculated the proportion of potential yield either as a percentage of the potential yield (Gayle *et al.* 1987), or as the amount of lost production in t/ha subtracted from the potential yield (Rudd and Chardon 1977). The maximum potential yield for sugarcane given under conditions limited by solar radiation at Ingham is 165 t/ha. (Muchow *et* *al.* 1991). This figure was used to calculate the potential sugarcane yield from the two yield models.

5.4.4.1 Gayle model

The Stress Day Index (Equation 5.19) was calculated for the 1997-98 season. It was necessary to raise the critical depth of waterlogging from the reported 45 cm (Gayle *et al.* 1987) up to 40 cm for the Gayle model to replicate the measured yields. The yield was calculated for the 1998-99 and 1999-2000 seasons and compared to the measured data for validation.

5.4.4.2 Rudd and Chardon model

The number of days in which the watertable was above 0.5 m was calculated and the figure of 165 t/ha (Murchow *et al.* 1995) was taken as the non limited potential yield to determine the modelled yield loss as a consequence of excess water on the growth of sugarcane.

5.5 RESULTS

5.5.1 Surface water modelling

5.5.1.1 SWMM

The simulated discharge data produced by SWMM was compared to the measured discharge data to see how well the catchment response was predicted by the numerical model. In the initial SWMM results the simulation did not accurately predict the peak flow rates very well (Figure 5.2). The resistance to flow was too great reflected in the Manning's n value of 0.31 and the simulated hydrograph did not match well with the measured hydrograph. The modelled peak flow rates were well below the measured peak flow rates (Figure 5.2).

The resistance to flow was decreased by decreasing the value of the Manning's n and, as expected, the simulated peak discharge increased. An optimum fit for the simulated discharge hydrograph was found when the Manning's n value was taken as 0.1 (Figure 5.3).

To test the goodness of fit, the RMSE should be as close to zero as possible and the Coefficient of efficiency (E), and Index of agreement (d) should be close as possible to 1.0. The best fit for the simulated discharge hydrograph was when the Manning's n was 0.1, corresponding to a RSME of 1.23, an E of 0.65, and a d of 1.00 (Figure 5.3, Table 5.3).

Table 5.4 Comparison of the goodness of fit of the measured discharge to the simulated discharge from the Palmas site. The best fit occurs when residual means square error (RMSE) =0, and d and E =1.0 (Legates and McCabe 1999)

Mannings n	0.035	0.09	0.1	0.11	0.12	0.15	0.31
RMSE	1.76	1.23	1.23	1.24	1.27	1.34	1.86
Coefficient of efficiency (E)	0.03	0.65	0.65	0.64	0.62	0.55	0.13
Index of agreement (d)	0.99	1.00	1.00	1.00	1.00	1.00	0.99

The peak discharge recorded on the 17 February 2000 was simulated well by SWMM (Figure 5.3, Table 5.4), the model predicted the discharge to be 0.018 m^3/m^3 while the measured discharge was 0.017 m^3/m^3. The model over predicted the runoff peak and the 15 February 2000 and under-predicted the peak discharge on the 19 February 2000 and on the 20 February 2000 (Fig 5.3). The model predicted a discharge event about midday on the 19 February 2000 (Fig 5.3) as 21 mm of rain fell. However there was no record of any discharge for this event.

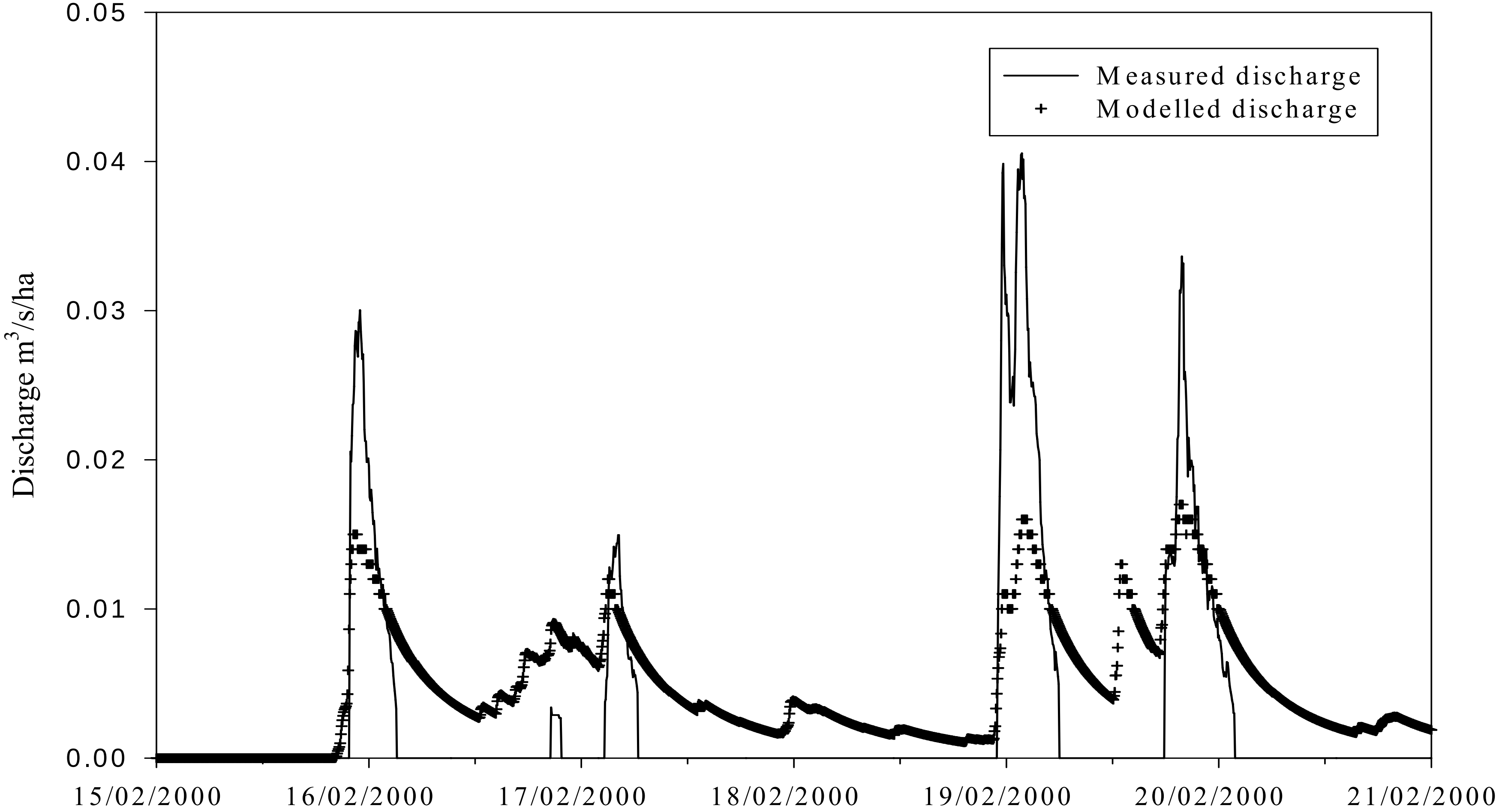


Figure 5.2 Measured discharge and SWMM modelled discharge (Mannings n=0.31) from the large field flume at the Palmas Site, 15-21 February 2000.

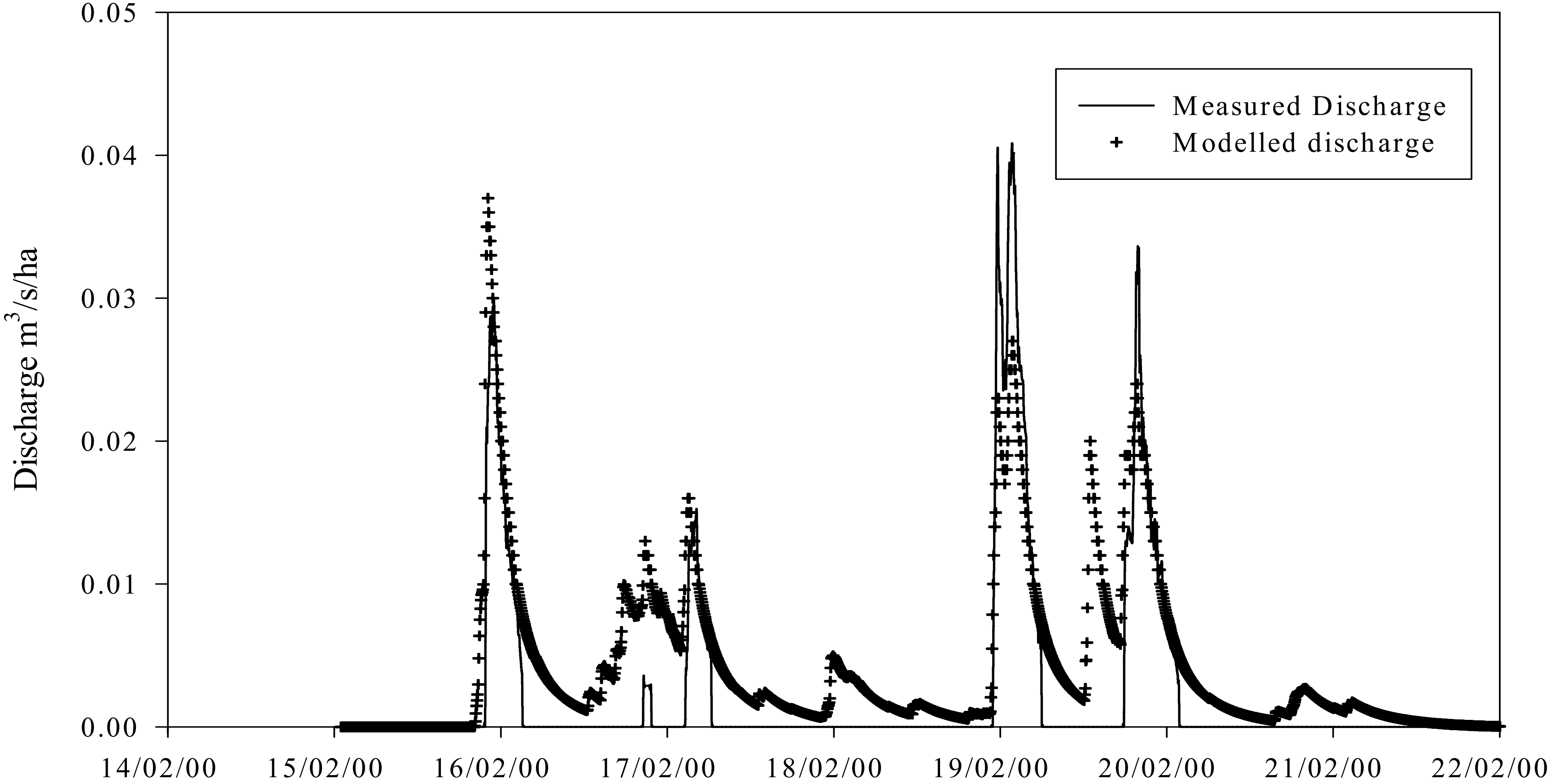


Figure 5.3 Measured discharge and SWMM modelled discharge (Mannings n=0.1) from the large field flume at the Palmas Site, 15-21 February 2000.

The tail of the modelled hydrograph matched the measured hydrograph very well (Fig 5.3), until the final part of the runoff event when the simulated hydrograph showed a more gentle recession as compared to the measured data (Fig 5.3). The sudden drop off in the measured hydrograph may be an artifact of the measurement device. The doppler meter requires a minimum depth of water of 50 mm and if the water level drops below this, then no velocity is recorded. A compound rectangular V-notch weir was installed to capture the low flows (Section 3.4) however it became very difficult to determine from the site recordings when the weir was submerged and when it was running freely.

There was a small discharge event measured late on the 16 February 2000. The model over predicted the discharge for that event in all simulations. A reason for this may be due to inaccuracies in the measurement of the flow event by the doppler meter as a result of the low flows.

No useful discharge data was measured from the Lasered Palmas site. However in section 3.4.1 a Manning's n of 0.31 was determined for the rows (Section 3.4.1). Using this value in the SWMM the runoff from the Lasered Palmas site could be simulated. The field was similar to dimensions as the Main Palmas site (Section 2.2). From these data the discharge hydrograph for the Lasered Palmas Site would be similar as the modelled discharge hydrograph in Fig 5.2.

5.5.1.2 Unit Hydrograph

The ordinates of the unit hydrograph (U; Equation 5.12) were calculated for two events 15 February 2000 (Fig. 5.4) and 17 February 2000 (Fig. 5.5) and the results were averaged (Table 5.5) The calibrated unit hydrograph produced for the 15 February 2000 fitted the observed data extremely well (Fig. 5.4), but there was some error in prediction towards the end of the second event (Fig. 5.5).

The averaged ordinates of the unit hydrograph (Table 5.4) were used to calculate the discharge hydrograph for the runoff event that occurred on the 3/04/99. The measured discharge hydrograph was compared to the calculated unit hydrograph and the latter fitted the measured data extremely well (Fig 5.6). Although there was some error in simulation of the peak discharge the event served to validate the averaged ordinates of the unit hydrograph (Figure 5.6).

Table 5.5 Ordinates of the unit hydrograph developed for the Palmas Site

	15/02/01	17/02/01	Average
Time (h)	Unit hydrograph U (L/mm)	Unit hydrograph U (L/mm)	Unit hydrograph U (L/mm)
0.5	1.27	1.12	1.19
1	0.68	1.38	1.03
1.5	1.58	1.35	1.46
2	0.20	0.85	0.53
2.5	1.20	0.82	1.01
3	0.001	0.66	0.33
3.5	0.80	0.54	0.67
4	0.40	0.54	0.47
4.5	0.29	0.47	0.38

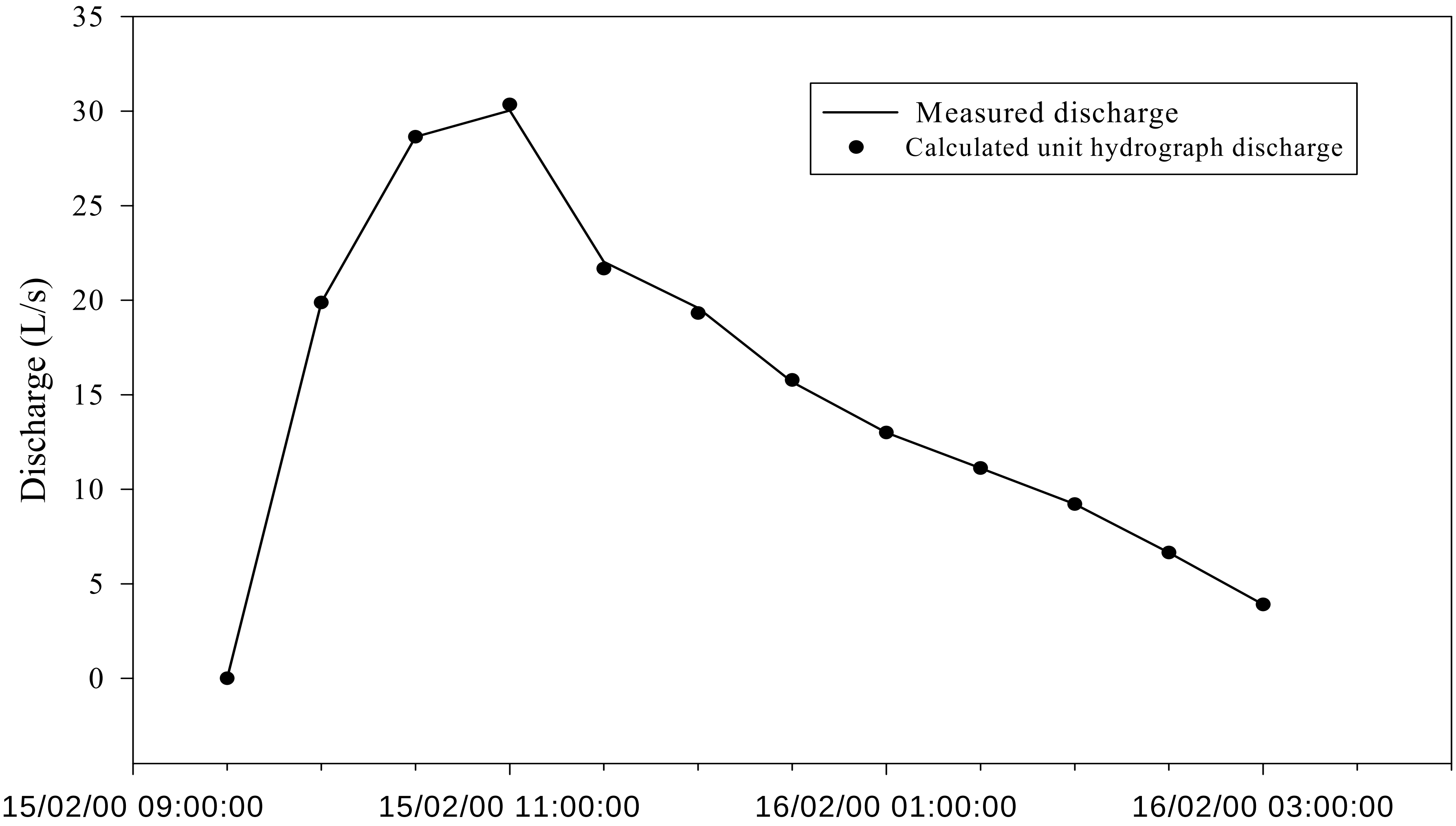


Figure 5.4 Comparison of the measured discharge with discharge calculated from the unit hydrograph, Palmas Site 15, 16 February 2000

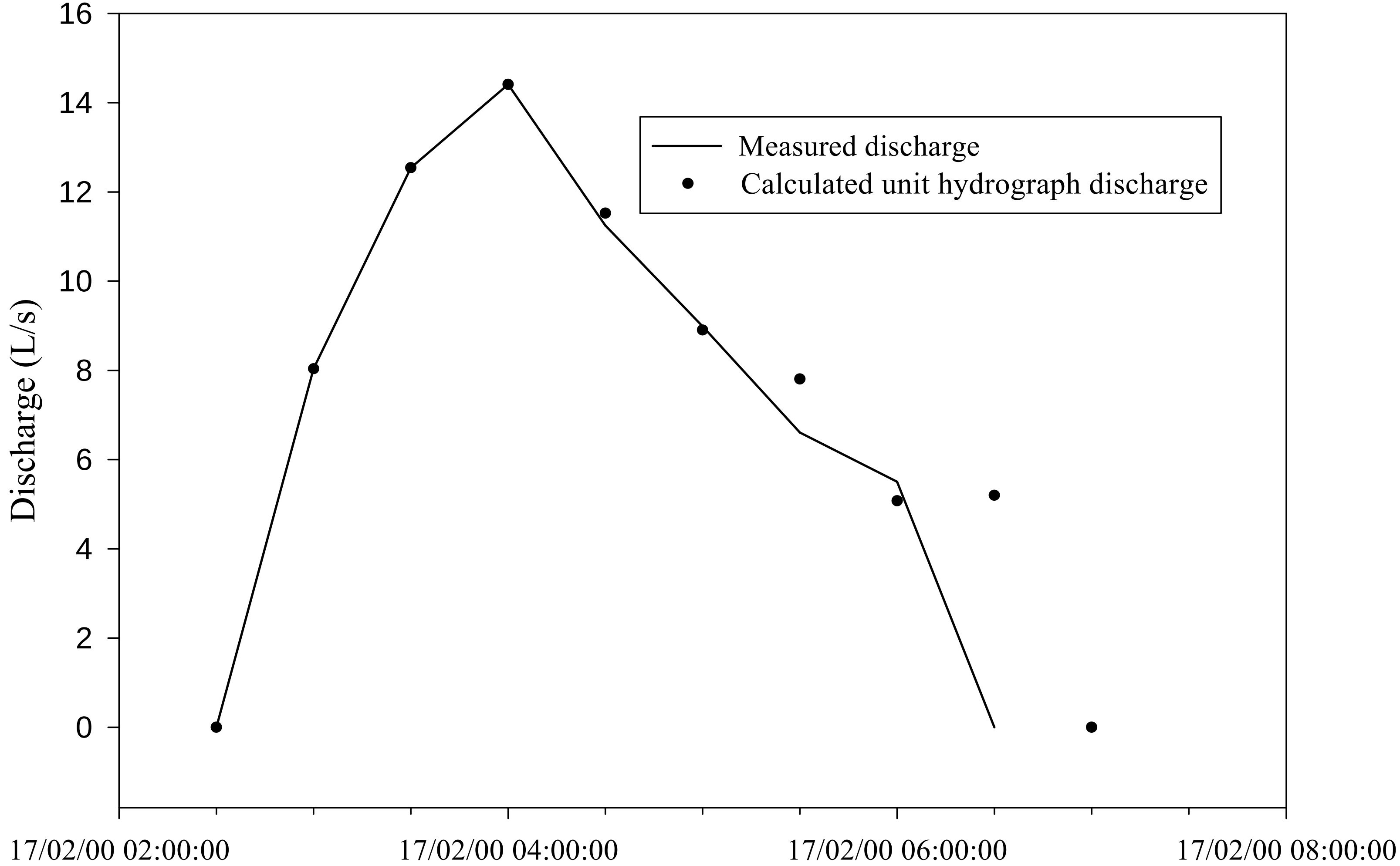


Figure 5.5 Comparison of the measured discharge with discharge calculated from the unit hydrograph, Palmas Site 15, 16 February 2000

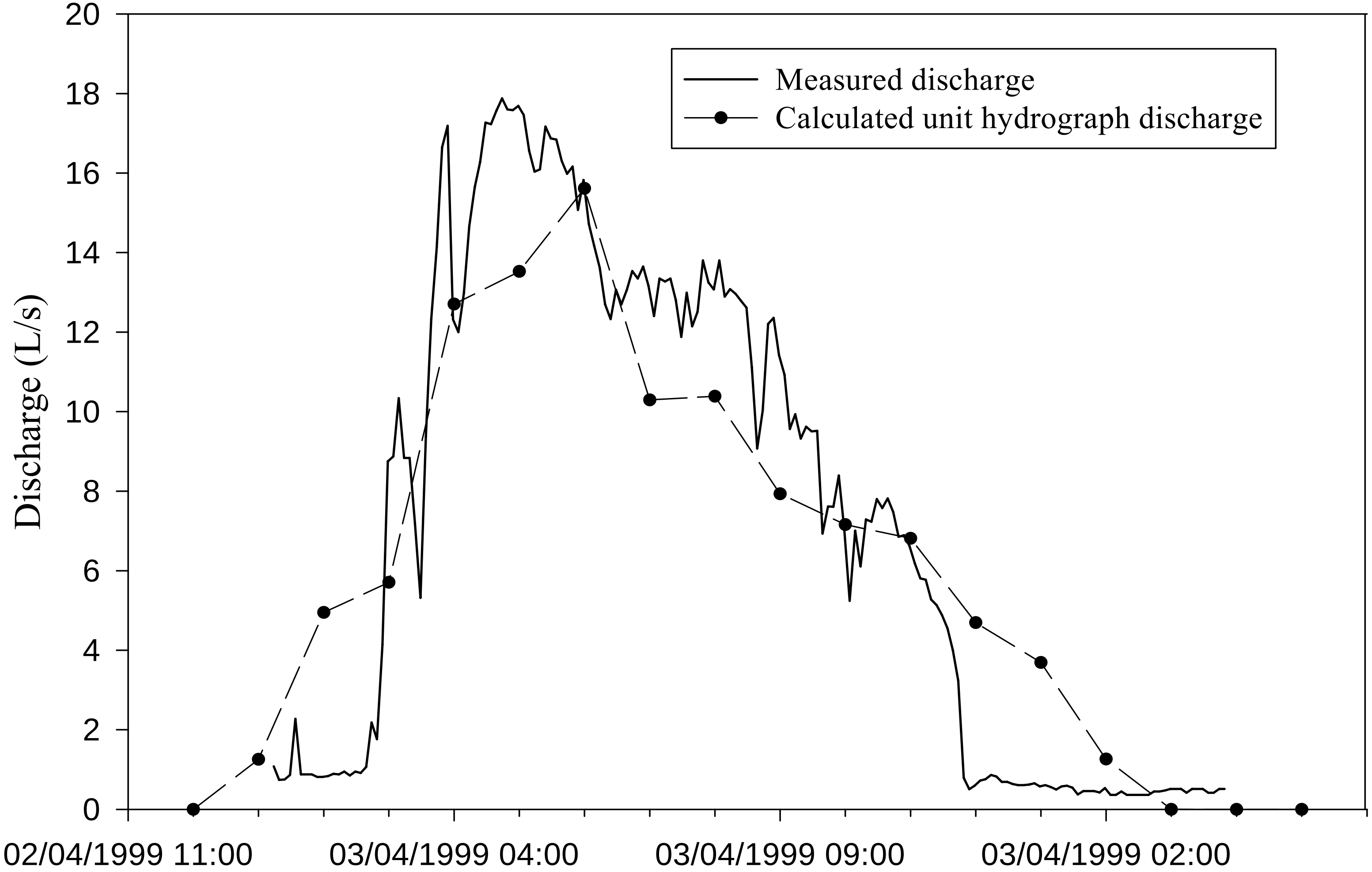


Figure 5.6 Validation of averaged unit hydrograph ordinates to predict discharge from a rainfall event at Palmas Site

5.5.2 Watertable modelling

The watertable model of Youngs *et al.* (1989) simulated the dynamics of the watertable over the two year observation period of the present study (Fig 5.7). The measured and modelled hydrographs closely match when tested by the coefficient of efficiency (E =0.59), and index of agreement (d =0.86). Other published data show that a value of E ranges from 0.53 (Holveot *et al.* 2005) to 0.7 (Zhang and Mitsch 2005), while a value of d ranges from 0.8 to 0.9 for a models (Covert *et al.* 2005; Zere *et al.* 2005) and up 0.94 (Ferrer-Alegre and Stockle 1999).

The objective of the watertable modelling was to simulate the temporal dynamics of the watertable and the prediction of waterlogging by shallow fluctuating watertables. The modelling results were analysed to determine how accurately the simulated watertable matched the maximum measured drawdown of the watertable and the period predicted waterlogging compared to the measured data.

For the first measure a subset of the two year dataset (Fig 5.8) was selected from August 1998 to June 1999 (Fig 5.9). This subset shows the ability of the model to simulate the dynamics of the watertable. The model simulated both the rapid rise of the watertable immediately after rain and the subsequent slow drawdown of the watertable. The model predicted the maximum depth of the watertable with some accuracy with the greatest difference occurring on the 9 December 1998 of 0.27 m. However the next greatest difference was 0.16 m on 11 June 1999 (Table 5.6). The average difference between the maximum modelled depth and maximum measured depth over the selected events was 0.03 m (Table 5.6).

The amount of waterlogging the model predicted as compared to the measured data was calculated as the number of days the of agreement between when the model predicted the watertable was above 0.5 m as compared to the measured data for the complete measurement period. Out of the 763 days of measurement the model wrongly predicted 33 days that the watertable was shallower than 0.5 m or the sugarcane was waterlogging when it was not and 35 days when the watertable was deeper than 0.5 m when the measured watertable was shallower than 0.5 m.

At greater depths in the soil the model under-predicted the depth of the watertable drawdown, but predicted the shallower watertable dynamics with some precision. This may be a consequence of the assumption of a constant specific yield over the drained layer; it is possible that the specific yield may vary at depth. There are periods where the model does not simulate this processes as well as others however overall it shows that a good spatial and temporal fit, as measured E and d, of the model results to the measured results.

Table 5.6 Differences between maximum measured and maximum modeled watertable depth

Date	Measured (m)	Modelled (m)	Difference (m)
22/09/1998	-0.13	-0.14	0.01
13/10/1998	-0.36	-0.45	0.09
1/11/1998	-0.32	-0.22	-0.10
9/12/1998	-0.57	-0.85	0.27
30/12/1998	-0.62	-0.52	-0.11
15/01/1999	-0.44	-0.36	-0.08
25/02/1999	-0.55	-0.48	-0.08
24/03/1999	-0.24	-0.19	-0.05
9/05/1999	-0.43	-0.36	-0.07
11/06/1999	-0.83	-0.67	-0.16
Average			-0.03

The departure of the modelled watertable dynamics from the measured watertable dynamics at depth, from June 1999 to November 1999 may also relate to the assumption that roots were actively extracting water (Fig 5.7). Sugarcane would be starting to regrow from the previous harvest and the roots may not be fully developed and cannot extract water from the relevant depth (Figure 5.7). Later in the same season the model did simulate the drawdown of the watertable (Figure 5.7), and there is good agreement in the following season between the modelled and the measured watertable data (Figure 5.7).

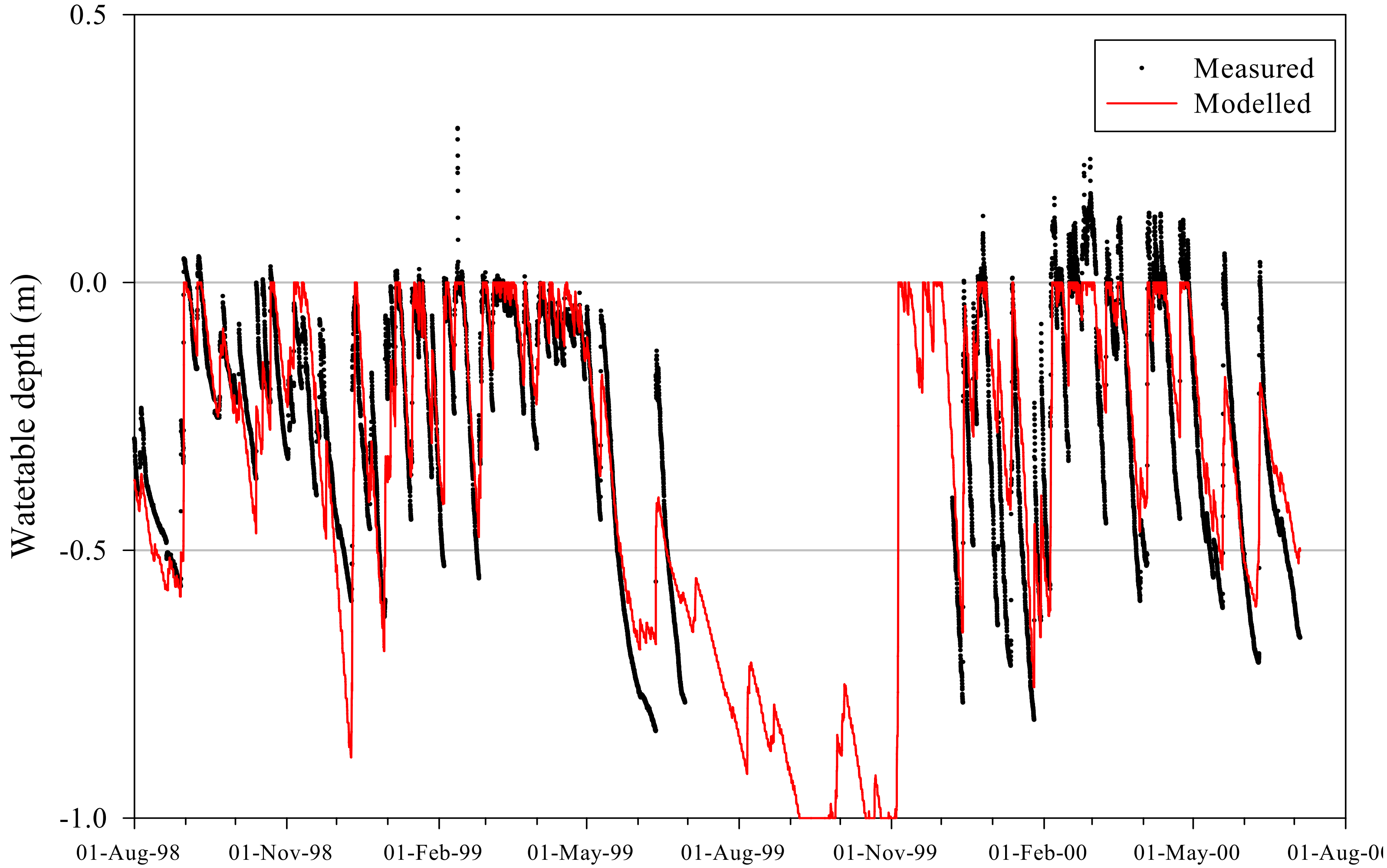


Figure 5.7 Comparison of the measured watertable response and the simulated response from the Youngs *et al.*(1989) model, Palmas Site August 1998-May 1999

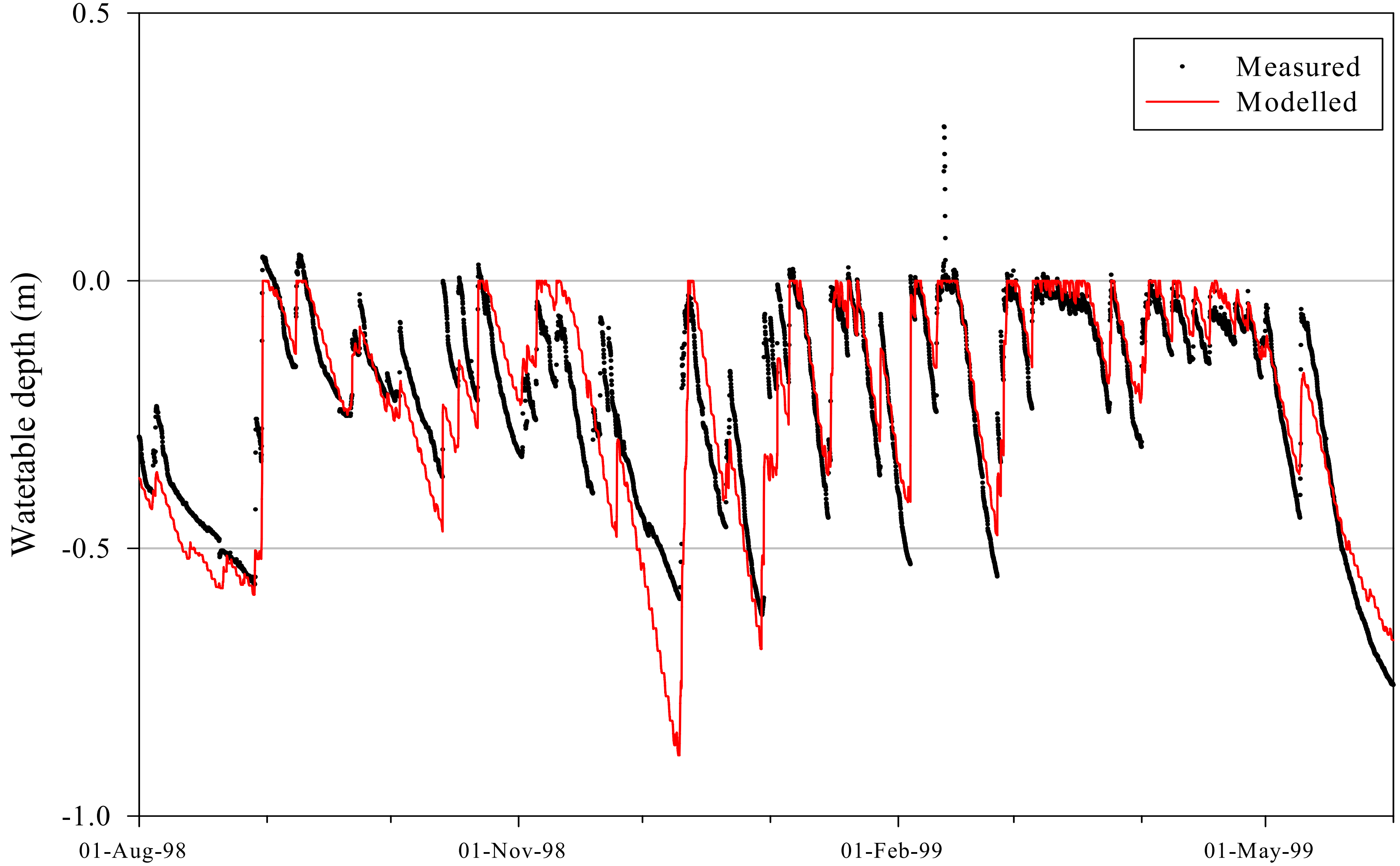


Figure 5.8 Comparison of the measured watertable response and the simulated response from the Youngs *et al*. (1989) model, Palmas Site August 1998-June 1999

5.5.3 Crop growth responses to excess water

The yield models both produced simulated sugarcane yields in close agreement with the measured sugarcane yield data (Table 5.7). The criteria for the Rudd and Chardon model was changed slightly, the original period for waterlogging stress was between December and July (Rudd and Chardon 1977), in the present study this was extended to the entire growing season. The critical water table depth in Gayle *et al.* (1987) model was changed from 0.45 m to 0.4 m to improve model predictions. This shallower depth produced a much closer fit between the modelled and the actual yields (Table 5.7). Both models predicted the yield reduction from a theoretical potential yield for the Ingham of 165 t/ha (Murchow *et al.* 1995).

Table 5.7 Comparison of measured and modelled sugarcane yield data from Main Palmas site

Year	Rain (mm)	Number of days watertable is shallower than 50 cm	Measured Yield (t/ha)	Modelled Yield (t/ha)	
				Rudd and Chardon	Gayle
1997-98	2596	179	86	83	80
1998-99	2153	281	44	36	44
1999-00	3018	185	80	80	64

The Rudd and Chardon model predicted the yield well, and there was very close agreement with the measured and the modelled data for all three seasons (Table 5.7). The Gayle model under predicted the yield in the 1999-00 season, but was very accurate for the very wet 1998-99 season (Table 5.7).

5.6 CONCLUSIONS

Due to the complex discharge regime measured in the main field flume at the study site it was initially thought that the algorithm used in SWMM to simulate the runoff could not simulate the dynamics of the surface water. However, it was found that the drainage system behaved as if the flow in the main large field flume could be simulated by assuming the water flow from the sugarcane field was being restricted by a high resistance to flow (i.e. high Manning's n). This approach was tested over two wet seasons and it was found that SWMM (Huber and Dickenson 1995) could be used to simulate the dynamics of runoff from the field, especially when a value of 0.1 was used for Mannings'n in the presence of a trash blanket (Fig 5.3).

The watertable model of Youngs *et al.* (1989) simulated the dynamics of the shallow fluctuating watertable over a period of 2 years of relatively high rainfall. The robustness of the measured soil hydraulic conductivity and the measured specific yield was demonstrated by the model's simulation of the measured watertable (Figs. 5.7-8). The model predicted the shallower watertable responses better than deeper watertable (Section 5.5.2).

The two sugarcane yield models proved to be reliable predictors of the biomass yield of sugarcane grown in soils with shallow fluctuating watertables (Table 5.7) for the three measured seasons. The Rudd and Chardon (1977) model was found to be an excellent predictor of the yield of sugarcane under conditions of excess water. Raising the critical watertable depth in the Gayle *et al.* (1987) model from 0.45 m to 0.4 m permitted a reliable predictor of biomass yield of sugarcane. Both models are empirical models that require no understanding of how the reduction of yield occurs.

The assumption underlying both sugarcane yield models is that there is a critical watertable depth and, if the watertable lies at a shallower depth, then there will be a reduction in sugarcane yield. The critical watertable depth of both sugarcane yield models is between 0.4 m and 0.5 m. Any drainage design that incorporates watertable control must aim to minimise the time the watertable lies at or above such a depth.

CHAPTER 6 DESIGN CRITERIA FOR SURFACE DRAINAGE OF SUGARCANE FIELDS

6.1 INTRODUCTION

"Surface drainage practices have largely developed from experience and observation rather than a basis of controlled research. However valid the current practices are, unless the physical processes that underlie surface drainage are understood then applying this empirical approach limits the surface drainage criteria to known areas and they cannot be extended to new and untested areas" (Edminister 1975)

In this chapter the results of the previous chapters are combined to develop criteria for surface drainage of low lying sugarcane fields in the wet tropics. Development of drainage criteria depends on a number of factors *viz*, the objective of the drainage criteria, the nature of the drainage system, and the economics of the farming system. In the present study it is required that the drainage system improves sugarcane productivity by the reduction of waterlogging and inundation. However that must be balanced against any decrease in drainage water quality, and economic viability of sugarcane production system.

Removal of surface water from fields was first thought to be the key to increased productivity of the sugarcane industry in the Lower Herbert Valley (C Roth pers comm.). The evidence from the present study suggests that waterlogging by shallow fluctuating watertables is the main cause of reduced productivity (Section 3.4.4), although removal of surface water is still central to improved drainage in the district. The previous chapters (Chaps 3-5) provide evidence that there extended periods of waterlogging up to, 157 days out of 207 (Section 4.4.2.1) as compared to inundation, as measured by τ, of between 1.2 to 7.6 hours (Table 3.7). The effect of waterlogging on sugarcane growth is examined in

Section 5.5.3 which suggests that the extended periods of waterlogging decrease the potential yield of sugarcane as compared to the potential yield by anywhere from 85-121 t/ha (Table 5.6).

Models were calibrated to simulate the physical processes of runoff and the watertable dynamics (Sections 5.4.1, 5.4.2). Two empirical models were used to simulate the crop yield response to fluctuations of the watertable (Section 5.4.3). These models can be used as predictive tools to determine field and crop responses to environmental and field design parameters. The present chapter focuses on understanding how different field designs will affect inundation of fields and waterlogging of soils which in turn will affect the sugarcane yield by simulation using the computer models presented in Chapter 5.

6.2 CURRENT DRAINAGE CRITERIA

The current drainage criteria in the Herbert Valley (Section 2.3.1) require, for the regional drainage system, that the "Main drains shall be designed to carry 85% of the volume of a three-day three-year event over a period of three days." (Gutteridge, Haskins and Davey 1976). This criterion was later revised to a modulus of drainage of 5 L/s/ha (Cameron McNamara 1984).

Currently there are no formal criteria to minimise waterlogging in sugarcane fields in the Lower Herbert Valley. However there is a range of practices that can be undertaken to minimise the risk of waterlogging.

6.3 METHODOLOGY TO DERIVE DRAINAGE CRITERIA

In this section the justification to derive drainage criteria is presented and several modelling scenarios are developed.

6.3.1 Criteria for the management of inundation

Surface water drainage criteria aim to remove excess water from a unit area of land over a set period of time at a rate that can be accepted by the regional drainage system. Inherent in these criteria is prevention of accumulation on the field of excess surface water from rainfall.

Initially it was thought that one of the main causes of lost productivity in the Herbert Valley was inundation of fields. The present study has found that the duration of inundation is relatively short; between 1.2 and 7.6 hr (Table 3.7, Section 3.4.4). This figure is much lower than the accepted industry figure of 3 days (Gutteridge, Haskins and Davey 1976). However, runoff from higher in the catchment fills the drains. In response to additional rain, the drains overflow and water in the field cannot discharge into the drainage system and the fields become inundated (Section 3.4.2). The current field design parameters (Section 2.3.1) aim to remove water as quickly as possible from the field, and this exacerbates the inundation of fields further downstream. The new optimised field design criteria should remove water as quickly as necessary, to avoid downstream flooding and at the same time, minimise the effect of inundation on sugarcane. This balances the exposure of plant's to excess water against the requirement that the runoff must be coordinated with the regional drainage system to avoid inundation on a regional basis. The previous chapters of this thesis have shown that the current discharge from the field is very complex and not only dependent on field design, but also on the pattern of flow from further upstream (Section 3.4.2). Under these conditions the discharge from the field can be estimated by a Manning's n of 0.1 (Section 5.5.1). Under the complex flow conditions, the field design parameters will not affect the characteristics of the runoff, such as peak flow rate and length of inundation, as the discharge from the field is controlled by the regional drainage system (Section 3.4.2). The true resistance to flow from fields with water furrows would be lower than the reported Manning's value of 0.1.

The first step in developing a more coordinated removal of water from the fields would be to remove the water furrows from the field design. The effect of this change would still have to comply with the drainage criteria to limit plant exposure to prolonged inundation, by ensuring that 85% of the surface water from a 3 day 3 year event is removed from the field in 3 days, and ensuring that the peak rate of runoff from a field is less than the amount required to inundate the regional drainage system.

The objective of the runoff criteria will be to reduce the peak flow rates to minimize the impact of the field drainage on the regional drainage system. Removal of water furrows may decrease the peak runoff rates by an increase in the hydraulic resistance. To determine the optimal field design parameters, for this environment, nine known runoff events were selected from the rainfall record (Section 3.4.2), and modelled using SWMM. In SWMM field slope, length, and surface resistance were changed, and the peak flow rates and the recession coefficients were recorded.

6.3.1.1 Management options

Nearly all of the sugarcane in the Herbert Valley is harvested by the green cane trash blanket system (Section 2.2.2). The hydraulic resistance of the green cane trash blanket was estimated as 0.31 (Table 3.4, Section 3.4.1). The first year of the crop cycle, without a trash blanket, can be simulated from the value of the hydraulic resistance with no trash, at 0.13 (Table 3.4, Section 3.4.1).

6.3.1.2 Slope of the field

The selected slopes for the modelling scenarios had to represent the range of slopes that could be encountered in the Lower Herbert Valley. The selection of field slope should encompass a continuous range of slopes so the runoff response to changing slope can be identified, and considered in the economics of landforming.

In a survey of sugarcane field designs for the floodplain soil in Lower Herbert Valley (Section 2.3.1; Park (1999) found that 89% of the design slopes ranged between 0.05 and 1.0%, up to 80% of the fields had slopes between 0.05-0.5% and the modal value for all the slopes was 0.01%. Park (1999) also reported that the average volume of soil moved for landforming was 290 m^3/ha, with 90% of designs moving less than 400 m^3/ha. These economic and biophysical requirements constrain the selection of slopes to practices that conform with both the economics of landforming, which is to move as little soil as possible, and to remove excess water as quickly as necessary. As reported in Section 3.4.2, the bulk of the excess water is removed within the 72 hour time limit before sugarcane yield reductions occur. Decreasing the slope would allow the water to remain on the field for longer and may ease the flooding of the over full regional system at times of high rainfall. A slope of 0.01% (1:10, 000) represents a very gentle slope and is the practical lower limit to field slopes (Park 1999). The practical upper limit for slope used in the model is constrained by economic factors outlined above and the risk of erosion; the steepest slope simulated was set at 0.5%. A value in the range between the two slopes was chosen as 0.12% as this was also the currently recommended field slope (Section 1.2.3).

6.3.1.3 Row length

The length of the field is determined by a number of factors (Section 2.3.1). For the Lower Herbert Valley, Park (1999) reported that the average maximum sugarcane row length was

380 m and the average minimum row length was 261 m. The modelled field lengths were selected to represent the range of possible practicable lengths that could be employed for surface drainage based on the review by Park (1999). The field lengths; chosen were 150 m, 300 m, 450 m. and, 600 m; the field size for the modelling set as 1 ha; and the field width was varied to fit the field lengths.

6.3.2 Management options to minimise waterlogging

The watertable management criteria should minimise the time that the watertable is within the sensitive depth below the soil surface. This requires initially the depth of the watertable to be kept below 0.5 m for as long as possible and the time the watertable is within 0.5 m of the soil surface be minimised.

Waterlogging by shallow, perched watertables occurs in low lying sugarcane fields in the Lower Herbert Valley for prolonged periods, often for months at a time (Section 4.4.2). The effect of the depth of the watertable is critical to the productivity of sugarcane (Section 1.2.8). There is incomplete knowledge of the mechanism for yield reduction in sugarcane exposed to shallow watertables, but the depth of the watertable in which yield reduction occurs is around 0.5 m (Section 1.2.8). In the present study, the watertable remained above 0.5 m for many weeks (Section 4.4.4). Sugarcane yields were affected by the presence of shallow watertables (Section 4.4.4). The critical depth to minimise the effect of a shallow watertable on the productivity of sugarcane appears to be no shallower than 0.5 m (Section 5.5.3). Hence, the drainage design will aim to maintain the watertable below 0.5 m for as long as possible.

The factors and processes that control the shallow fluctuating watertable in heavy textured far levee soils, such as those at the Palmas Site, are the low saturated hydraulic conductivity of the lower soil horizons (Section 4.5.1), high rainfall, and evapotranspiration of the crop (Section 4.5.2). The measurement of interflow to shallow drains revealed that the amount of water that drained from the watertable was small (9% of the rainfall) compared to other sinks terms in the water balance (Section 4.4.2). The soil water drained to the water furrows from the watertable did not significantly reduce the duration or impact of waterlogging on sugarcane (Section 4.5.3). The removal of the water furrows from the field design will increase the area for cane production by 15% and the removal of the drains should have no significant effect on the watertable and hence sugarcane yield.

6.3.2.1 Modelling scenarios for waterlogging

The modelling options that were identified to develop optimised drainage criteria for the Lower Herbert Valley include the following four factors.

- ***Retention or elimination of water furrows***

Decreasing the distance between the water furrows may drain the watertable in a more timely fashion than with the current drain spacings; this may reduce the amount of time the watertable is within 0.5 m. But this scenario will require more productive area to be used as drains. Closer drain spacing could be achieved by installation of sub-surface drainage at the current or closer drain spacing. However sub-surface drainage may not be economically feasible. Either option, closer surface or sub surface drain spacing than the current spacing, may invalidate the Dupuit-Forchheimer assumption of parallel streamlines (Section 4.2.2). This assumption is inherent in the Youngs *et al.* (1989) model and for this reason such a scenario was not explored further.

If water furrows are ineffective in removing soil water from the watertable, then removal of the water furrows will increase the amount of area available for production. However, removal of water furrows may increase the length and severity of inundation and waterlogging. The effect of increasing the water furrow spacing can be simulated using the Youngs *et al.* (1989) model by substitution of a large distance for the drain spacing parameter (D), the subsequent effect of the watertable dynamics on the yield of sugarcane can be simulated by the two watertable yield models (Section 5.5.3; Rudd and Chardon 1977; Gayle *et al.* 1987).

- ***Mounding***

The individual cane rows are mounded by moving soil from the interrow space to the row. This adds 100 mm to the height of the row which in turn increases the drained depth of soil. Hence mounding of the rows would effectively decrease the predicted watertable depth by 100 mm. This can be very simply simulated by subtracting 100 mm from the predicted watertable depth.

- ***Waterlogging tolerance of sugarcane***

The emphasis of the present study has been on the physical processes that control the watertable depth. One of the processes is evapotranspiration (Section 4.5.3). If sugarcane could be bred to have greater waterlogging tolerance then this would be reflected by increased growth. This in turn can be simulated by increased evapotranspiration, which could be simulated by increasing the value of the crop coefficients (Kc). Although this is a very simple approach it is the basis of simulation of waterlogging tolerance developed by Feddes *et al.* (1978). In the model the onset of waterlogging stress is simulated by the reduction in root water uptake (Feddes *et al.* 1978). This in turn will reduce evapotranspiration; conversely a waterlogging tolerance will be reflected by an increase in root water uptake as compared to the stressed plant and a higher evapotranspiration. This can be simulated by higher crop coefficients. The effect of increased evapotranspiration on the dynamics of the watertable can be simulated with the Youngs *et al.* (1989) model.

- ***Plant or harvest date***

Sugarcane is more sensitive to high watertables earlier in its growth cycle than later (Gayle *et al.* 1987). The yield reduction model of Gayle *et al.* (1987) has a higher crop susceptibility factor for the first 130 days of growth. Planting or harvesting early will allow the plant to establish in the drier period between July and November and to avoid heavy rainfall and possible waterlogging in the sensitive 130 day establishment period. Five dates were selected during this period to represent the range of possible plant/harvest dates, 15 July, 15 August, 15 September, 15 October and 15 November. Plant growth responses can be simulated by the changing the dates of the simulated harvest/planting of the crop by adjusting the crop susceptibility factor (CS) to reflect the different planting and harvesting dates.

6.4 SIMULATION AND RESULTS ANALYSIS METHOD

6.4.1 Runoff

The runoff module in SWMM (Huber and Dickenson 1995) was used to simulate the field design parameters outlined in Section 6.3.1. The peak runoff rates from each modelling run was determined, and the recession coefficients (τ) (Post and Jakeman 1996) were calculated. Eight known runoff causing rainfall events were selected (Table 6.1). Five minute rainfall data was derived from the tipping rain gauge situated at the Palmas Site (Section 2.1.2). Peak discharge rates and recession coefficients (τ) from the modelling results were recorded for each different field design. The average peak flow rate and recession coefficient were calculated for the range of field design parameters over the eight runoff casing rainfall events.

A first order inverse polynomial equation (Equation 6.2) was fitted to the observed peak runoff rate data and field length, using SigmaPlot 2000 software;

$$f = y0 + \left[\frac{a}{x}\right]$$ Equation 6.1

where
f is the peak flow rate (L/s/ha)
x is the field length (m)
y0 is a fitted value
a is shape parameter

A linear equation was fitted to the observed recession coefficient data and field length, using SigmaPlot 2000 software (Equation 6.2)

$$f = y0 + a * x$$ Equation 6.2

where
f is the recession coefficient (hr^{-1})
y0 are fitted values
x is the field length (m)
a is shape parameter

6.4.2 Watertable

The watertable scenarios outline above (Section 6.3.2) were modelled with the Youngs *et al.* (1989) model between 1991-2000 from weather data measured at Macknade mill (M. Spillman, pers, comm.). The model parameters were changed to reflect the field design and plant modifications described above (Section 6.3.2). The watertable response was calculated between the three different plant /harvest dates, and for the presence or absence of water furrows.

The number of days the watertable was above 0.5 m was calculated and the average for the treatment was plotted against; growing season rainfall, the amount of rain that fell between the plant date and the following harvest date; the wet season rainfall, the amount of rain that fell between December and April, and; rainfall that fell between 0 and 130 days after plant date.

The statistical tools in SigmaPlot 2000 were used to fit a linear function namely;

$$f = y0 + a * x$$ Equation 6.3

where
f is the dependent variable
x is the independent variable
y0 are fitted values

6.5 RESULTS OF MODELLING SCENARIOS

6.5.1 Inundation

6.5.1.1 The effect of trash blanket on the peak runoff flow rate

The removal of the trash blanket from the field increased the field's response to rainfall with the average modelled peak flow rate of the trash blanketed treatment being 16 L/s/ha, while the non trash blanketed rate was 24 L/s/ha (Fig 6.1; Tables 6.1, 6.2). The peak flow rates for all of the trash treatments were lower than that of the same treatment without a trash blanket. The trash blanket had more effect on the shorter rows and the higher slope treatments. As the field length increased and the slope decreased, the effect of the slope became less pronounced (Fig 6.1; Tables 6.1, 6.2).

The range of simulated flow rates from both treatments show that high volumes of runoff water are delivered to the regional drainage system. In the non trash blanketed field the highest peak flow rate was 98 L/s. Flow rates of this magnitude were measured in 2000 (Section 3.4.2.2) but only when there was extensive flooding of the area. The same rainfall event produced a peak flow rate of 59 L/s from the trash blanketed field. This discharge is still considered to be very high, and may contribute to extensive local flooding. The same rainfall under different field designs simulated a peak flow of 8 L/s/ha. The lowest simulated flow rates of 2 L/s occurred in the trash blanketed field, the comparative flow rate for the non trash blanketed flow rate was 5 L/s (Tables 6.1, 6.2; Figs 6.1. 6.2).

Table 6.1 Simulated peak flow rates (L/s) from a 1 ha field without a trash blanket and with different lengths and slopes from eight runoff causing rainfall events (Manning's n=0.13).

Date	Slope	0.010%				0.125%				0.50%				Average
	Length (m)	150	300	450	600	150	300	450	600	150	300	450	600	
12/12/1998		23	16	12	10	35	29	25	22	46	35	31	29	26
06/1/1999		18	16	15	13	31	21	18	18	41	31	25	21	22
19/1/1999		25	14	10	8	64	40	28	22	98	66	49	40	39
13/2/1999		18	14	12	10	26	21	19	18	39	26	23	22	21
27/2/1999		19	13	10	8	30	24	20	17	36	30	28	36	23
06/3/1999		10	7	10	5	21	15	11	10	30	22	17	15	14
08/3/1999		18	12	10	9	33	24	11	17	45	34	28	25	23
02/4/1999		8	5	4	3	18	12	19	7	27	18	23	27	14
Average		19	13	11	9	34	25	20	18	48	35	29	27	24

Table 6.2 Simulated peak flow rates from a 1 ha field with a trash blanket with different legnths and slopes from eight runoff causing rainfall events (Manning's n=0.31).

Date	Slope	0.010%				0.125%				0.50%				Average
	Length (m)	150	300	450	600	150	300	450	600	150	300	450	600	
12/12/1998		15	9	7	5	27	21	16	14	33	28	23	21	19
06/1/1999		15	13	12	10	19	17	16	15	29	19	18	29	18
19/1/1999		12	7	5	4	35	20	13	11	59	36	25	20	23
13/2/1999		13	9	7	6	21	17	14	12	25	21	18	25	17
27/2/1999		12	7	5	4	23	16	12	11	29	23	19	16	16
06/3/1999		7	4	3	2	13	9	7	6	20	13	10	9	9
08/3/1999		11	9	8	7	23	15	13	11	32	23	19	15	16
02/4/1999		8	5	4	3	18	12	9	7	27	18	14	12	12
Average		12	8	6	5	22	16	13	11	32	23	18	18	16

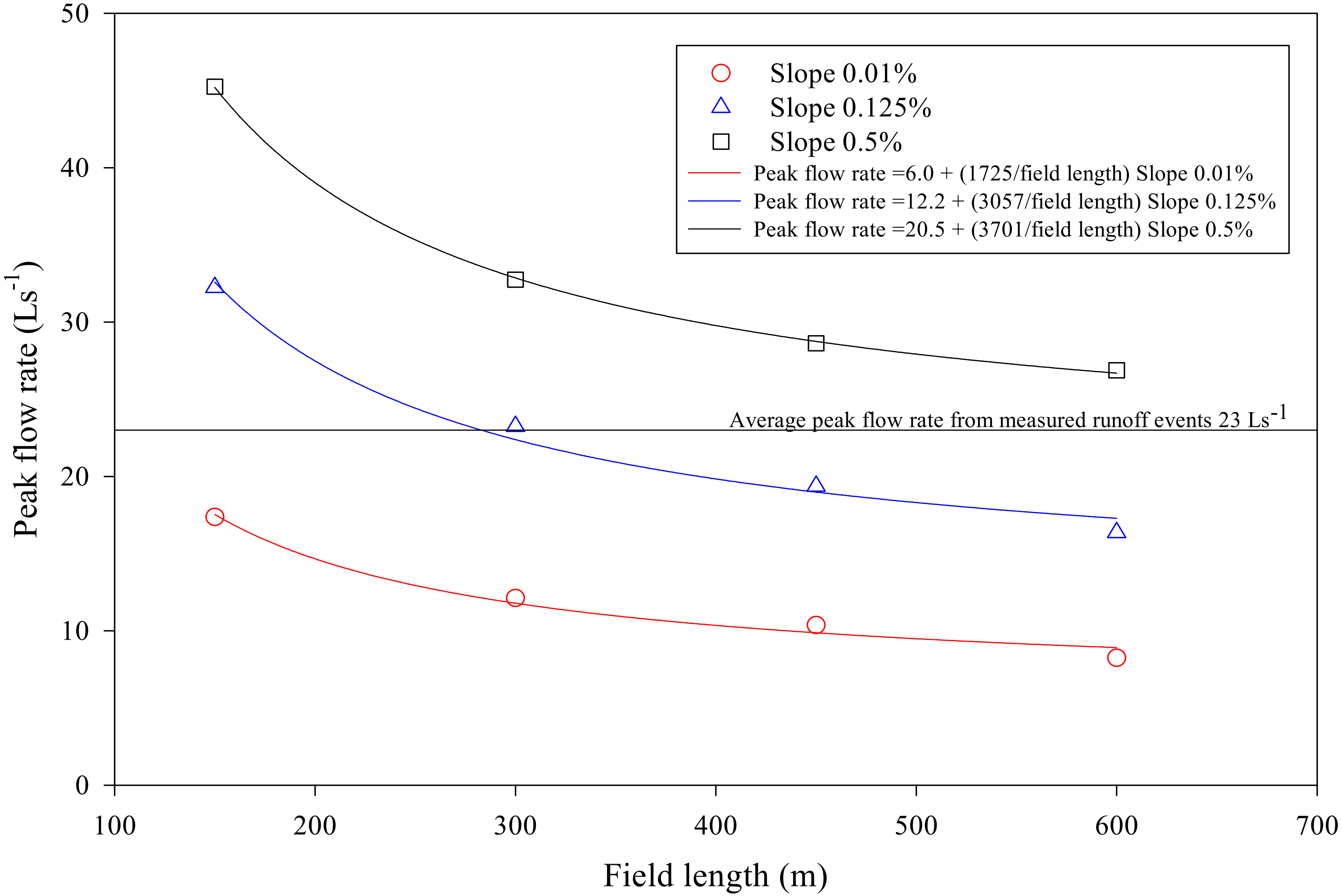


Figure 6.1 Average simulated peak flow rates from a 1 ha field without trash present and different field design parameters

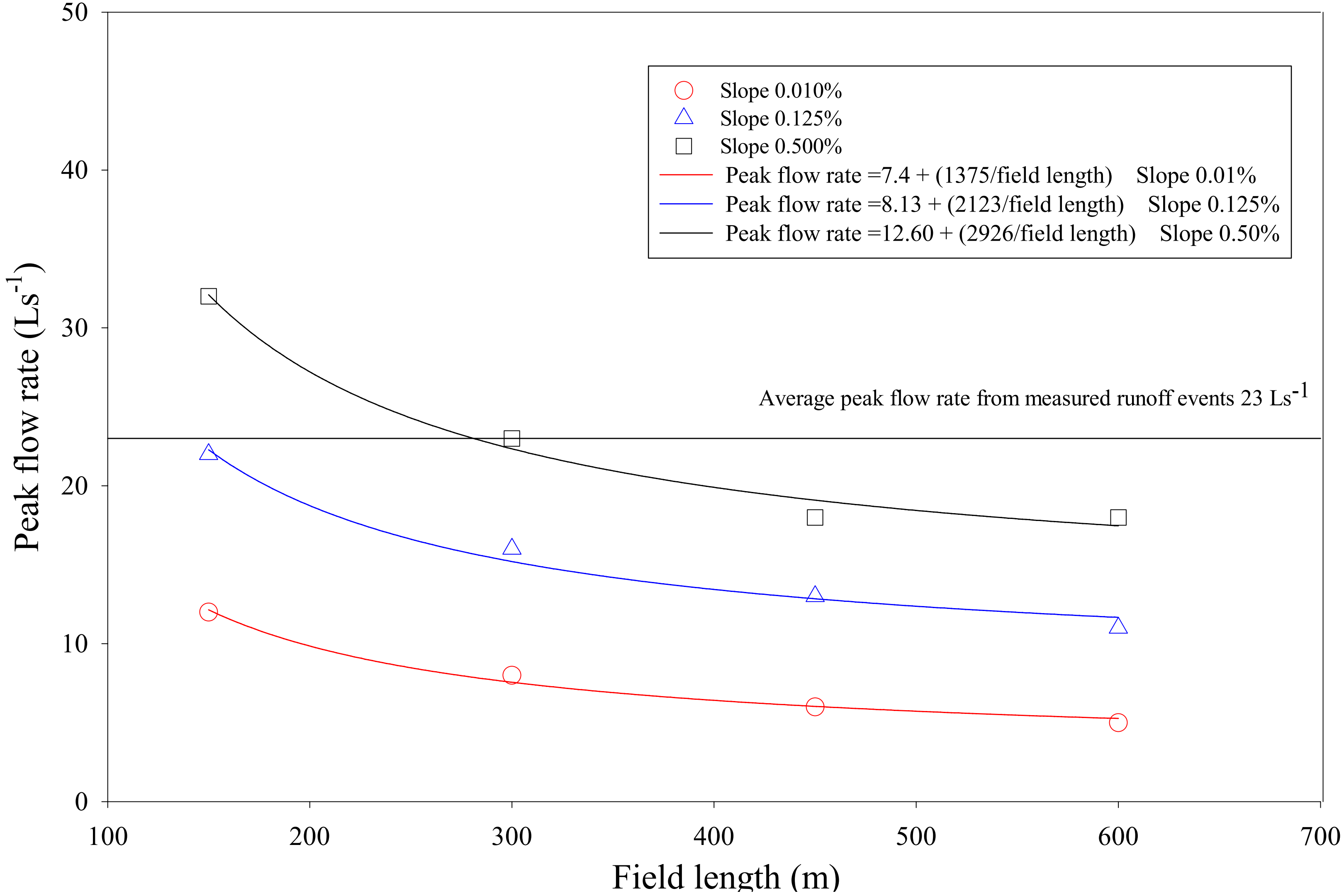


Figure 6.2 Average simulated peak flow rates from a 1 ha field with trash present and different field design parameters

6.5.1.2 *Effect of slope on peak flow rate*

Increased field slope increased the simulated peak discharge (Fig 6.1, 6. 2; Tables 6.1-2). The shorter row length combined with the steeper slope produced higher peak flow rates compared to fields with the same slope and greater field lengths. The highest peak flow rate occurred at the shortest field length, steepest slope and with no trash blanket, while the lowest peak flow rate occurred at the longest field length, flattest slope and with a trash blanket (Fig 6.1, 6. 2; Tables 6.1-2).

An average peak runoff rate of 24 L/s/ha was simulated at 0.5% slope from the three field lengths with trash present compared to an average of 8 L/s/ha at a slope 0.01% from the three field lengths and with a trash blanket present (Fig 6.1, 6. 2; Tables 6.1, 6.2). Hence the steeper field slopes may increase the risk of flooding of the regional drainage system and this may be independent of the field length or the trash management (Fig 6.1, 6-2; Tables 6.1, 6.2).

6.5.1.3 *Effect of field length on peak flow rates*

The simulated peak flow rates were also affected by the length of the field with the flow rates much higher for the shorter row lengths as the runoff had a shorter distance to travel and could leave the field faster (Fig 6.1; Tables 6.1, 6.2). Very high peak runoff rates were predicted for the steeper slopes, and no trash blanket and short field lengths with an average peak flow rate of 46 L/s/ha (Fig 6.1; Tables 6.1, 6.2). The longer the field lengths, the lower the peak flow rates, and the smaller the range of predicted flow rates. Increasing the field length reduced the ability of the field to drain high rates of drainage water to the regional system. The effect of trash appeared to outweigh the effect of field length on the peak flow rates. The predicted flow rates from the field without trash were similar to that of the fields half of the length with trash (Fig 6.1).

An inverse first order polynomial function was fitted to the average of the simulated peak flow rates for the individual slopes. The function was fitted to the six combinations of slope and trash management. All the fitted functions returned a adjusted r^2 of between 0.97 to 0.99 (Appendix A3.1). The individual functions related simulated peak flow rates to field length for a particular trash management option and a field slope.

The data and the fitted functions suggests that at a field length greater than 300 m slope there is only a small influence of field length on peak flow rate (Figs 6.1, 6. 2). The function also suggests that field lengths greater than 300 m would have only a small influence on peak flow rates.

6.5.1.4 Effect of trash blanket on recession coefficients

The calculated recession coefficient (τ) shows the time when 63% of the water is drained from the field (Section 3.3.2.6). The average recession rate in the current field design at the main Palmas study site is 4.4 hours (Section 3.4), which is well below the time at which inundation damage will begin. The highest average recession coefficient of 16 hours was found to relate to the flattest slope, longest field length and with a trash blanket present (Fig 6.3; Tables 6.3, 6.4).

The removal of the trash blanket decreased the recession coefficient (Fig 6.3; Tables 6.3, 6.4). However, the effect of the trash blanket was only noticeable on the low slopes and at short field lengths. All the calculated recession coefficients for the simulated fields were well below the 72 hour (3 day) threshold beyond which a decrease in sugarcane yield may occur.

Table 6.3 Recession coefficients from a 1 ha non trash blanketed field of different lengths and slopes from eight runoff causing rainfall events (Manning's n=0.13)

Date	Slope	0.010%				0.1250%				0.50%				Average
	Length (m)	150	300	450	600	150	300	450	600	150	300	450	600	
12/12/1998		3.7	6.4	9.6	16	1.7	2.6	4.0	3.8	1.3	1.7	2.3	2.6	4.6
06/1/1999		4.6	7.3	12.5	15.7	1.9	2.8	3.8	4.9	1.3	1.9	2.4	5.7	5.4
19/1/1999		5.1	6.4	5.5	12.3	0.2	3.3	4.8	5.8	0.8	1.3	2.7	3.4	4.3
13/2/1999		4.7	6.2	5.3	10.4	3	3.4	5.8	4.5	5.9	3.5	4.0	5	5.2
27/2/1999		3.1	6.7	5.3	14.7	2.4	3.4	7.5	4	3.2	2.4	4.6	3.6	5.1
06/3/1999		5.5	8.4	8.8	12.6	2.7	3.8	7.5	5.9	2.8	3.7	4.6	3.8	5.9
08/3/1999		4.4	6.9	12.5	9.3	4.7	4.3	5.6	5.3	4.2	4.6	5.5	4.2	6.0
02/4/1999		11.5	20.7	15.8	23.5	5	8.4	14.4	22.4	0.7	4.8	5.1	3.7	11.3
Average		5.3	8.6	9.4	14.3	2.7	4	6.7	7.1	2.5	3	3.9	4	6.0

Table 6.4 Recession coefficients from a 1 ha trash blanketed field of different legnths and slopes from eight runoff causing rainfall events (Manning's n=0.31).

Date	Slope: 0.010%				0.1250%				0.50%				Average
Length (m)	150	300	450	600	150	300	450	600	150	300	450	600	
12/12/1998	6.7	16.1	7	*	3.7	4.6	7.1	6.8	1.7	2.7	4.0	4.5	5.9
06/1/1999	7.6	10.2	7.7	13.5	6.5	5.3	8.4	8.1	2.7	3.4	3.8	4.2	6.8
19/1/1999	6.9	11.9	9.6	18.3	3.8	5.9	15	6.8	2.4	3.6	5.2	6.0	7.9
13/2/1999	7.2	10.3	8.3	13.8	3.7	5.1	19	6.8	3.2	3.5	4.3	3.2	7.4
27/2/1999	6.9	14.2	8.3	*	3.6	4.7	6.2	6.7	2.7	3.5	4.3	5.1	6.0
06/3/1999	9.3	9	8.3	*	4.2	5.9	9.3	8.5	3.8	5.6	4.2	5.7	6.7
08/3/1999	6.5	10.2	6.5	20.8	3.8	5.9	15	7.4	4.8	3.7	4.5	5.7	7.9
02/4/1999	23.5	28.7	17.8	36	5.9	11.1	25.4	22.4	3.7	5.7	14.1	10.0	15.0
Average	9.3	13.8	9.2	20.5	4.4	6.1	14.2	9.2	3.1	4.0	5.6	5.6	8.0

*No recession coefficient could be calculated for the simulated at 0.01% slope, 600 m long trash blanketed field due to the low flows that occurred.

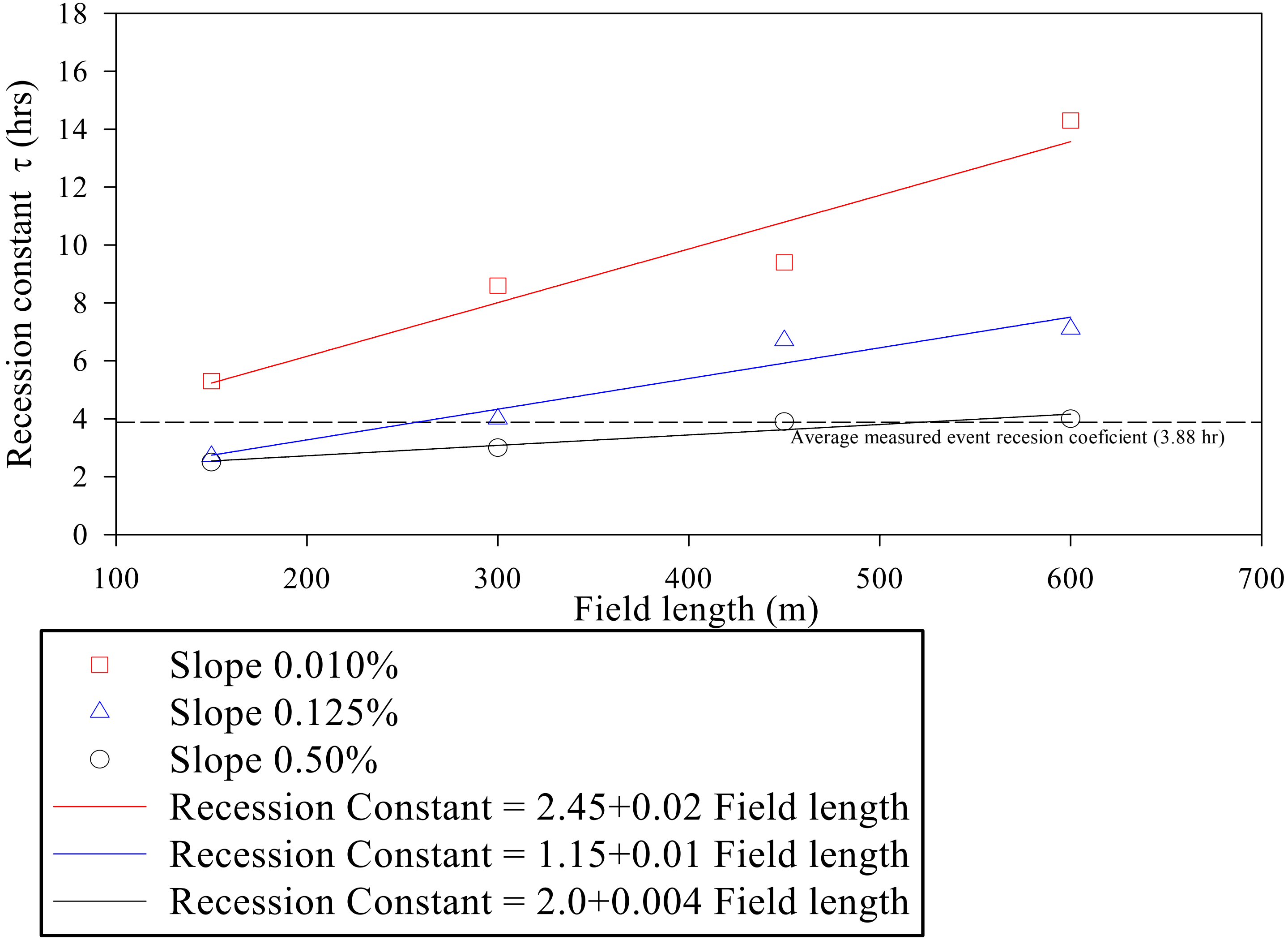


Figure 6.3 Average simulated recession coefficient (τ) from a 1 ha field with trash present and different field design parameters

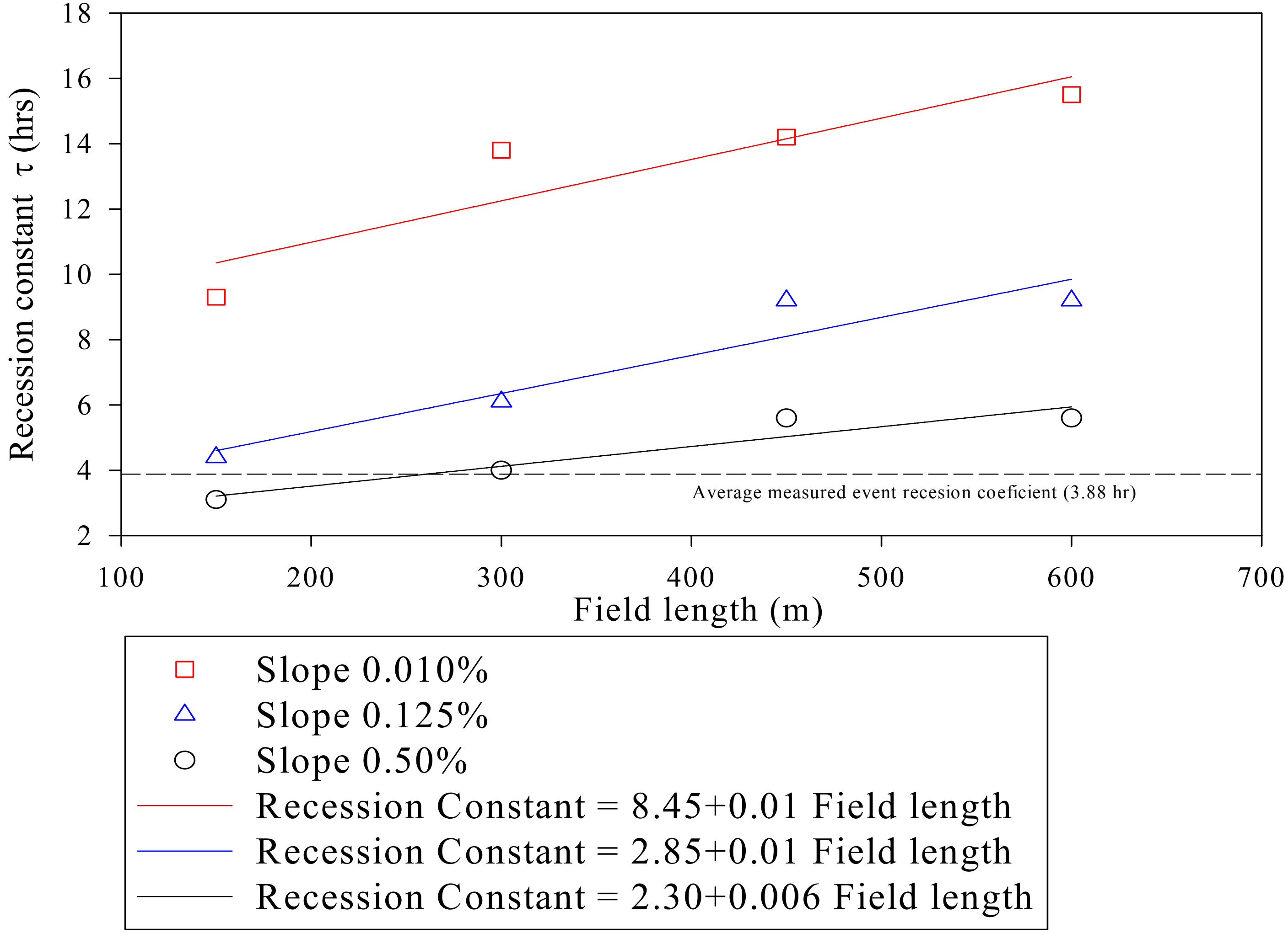


Figure 6.4 . Average simulated recession coefficient (τ) from a 1 ha field without trash present and different field design parameters.

The recession coefficient calculated from a simulation of a rainfall event on the 2 April 1999, for a long, low slope trash blanketed field (0.01%, 500 m) was 36 hours. These design parameters would cause the water to drain very slowly from the field and such combination should be avoided.

6.5.1.5 Effect of slope on recession coefficients

The flattest slopes affected the simulated recession coefficient the most (Figs 6.4, 6.5) and the recession coefficient was quite insensitive to slopes greater than 0.125% with no great difference in τ between the slopes of 0.125% and 0.5%.

6.5.1.6 Effect of field length on recession coefficients

The field length increased the value of the simulated recession coefficients (Figs 6.4, 6.5), nevertheless, it was only the lower slope of 0.01% that was found to be greatly influenced by field length. Most of the simulations produced recession coefficients above the current value of 4.4 hours, albeit marginally, but overall the effect of field length had only a small effect on the value of the recession coefficient (Figs 6.4, 6.5; Table 6.3, 6.4).

A linear function was fitted to the average simulated recession coefficients for the six combinations of slope and trash management. The fitted functions returned an adjusted r^2 between 0.89 and 0.90 for the treatments without a trash blanket (Manning's n of 0.31), while the functions fitted to the trash blanketed treatments returned an adjusted r^2 between 0.74 and 0.85 (Appendix A3.2).

The individual functions relates simulated recession coefficient to field length for a particular trash management option and field slope. This function suggests that there is a linear increase in the length of time the water remains on the field and the length of the field.

6.5.2 Watertables

The watertable model used rainfall data and simulated nine consecutive years at an hourly time step and the modelled watertable response was analysed. The watertable depth calculated at 12:00 am was taken as the daily average for the watertable depth. The results are presented in a number of ways. Initially the watertable response over the nine years was analysed on the basis of:

number of days of waterlogging (watertable above 0.5 m) over the growth season,

number of days of waterlogging between 1st December and 31st April (wet season),

number of days of waterlogging after 130 days of plant/harvest.

The data are also presented initially as a time sequence indicating a simulated watertable response to rainfall from 16 September 1991 to the 15 September 2000 (Fig 6.5). The modelled watertable responses are also displayed as a frequency distribution (Fig 6.6) indicating the frequency of accumulated the watertable response above a certain depth. The data is presented for the days the watertable was above 0.5 m in response to rainfall (Fig 6.7).

The watertable response was then divided into the growth seasons as defined by the five harvest/plant dates (Section 6.3.2.1), presence or absence of water furrows. The data presented is an average of the individual nine years over the five plant/harvest dates.

Finally, the two sugarcane yield models were applied to the simulated watertable response and the yield was modelled for the five different plant/harvest dates and the presence or absence of water furrows.

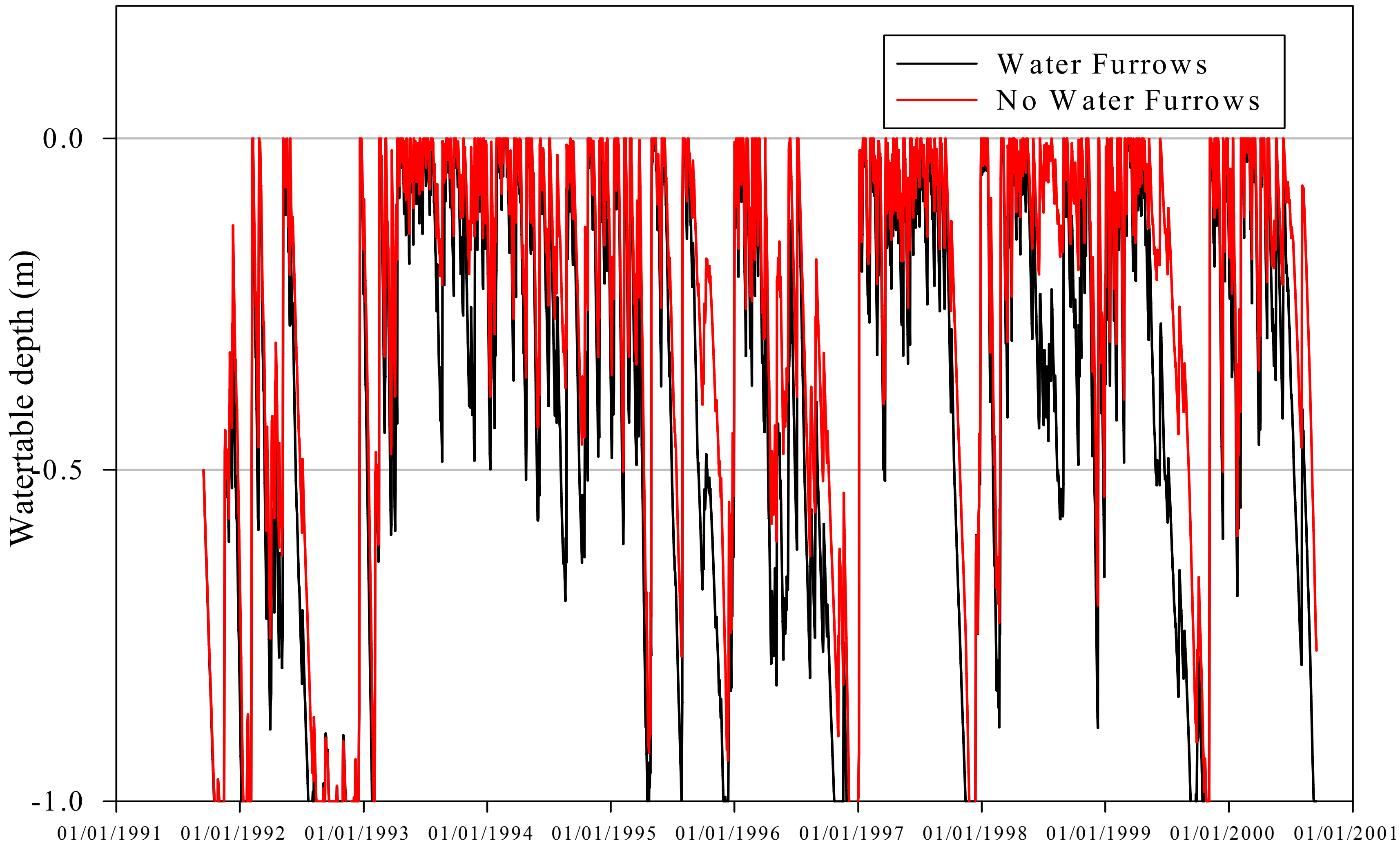


Figure 6.5 Two modelled watertable responses, with and without water furrows from 16 September 1991 to 15 September 2000

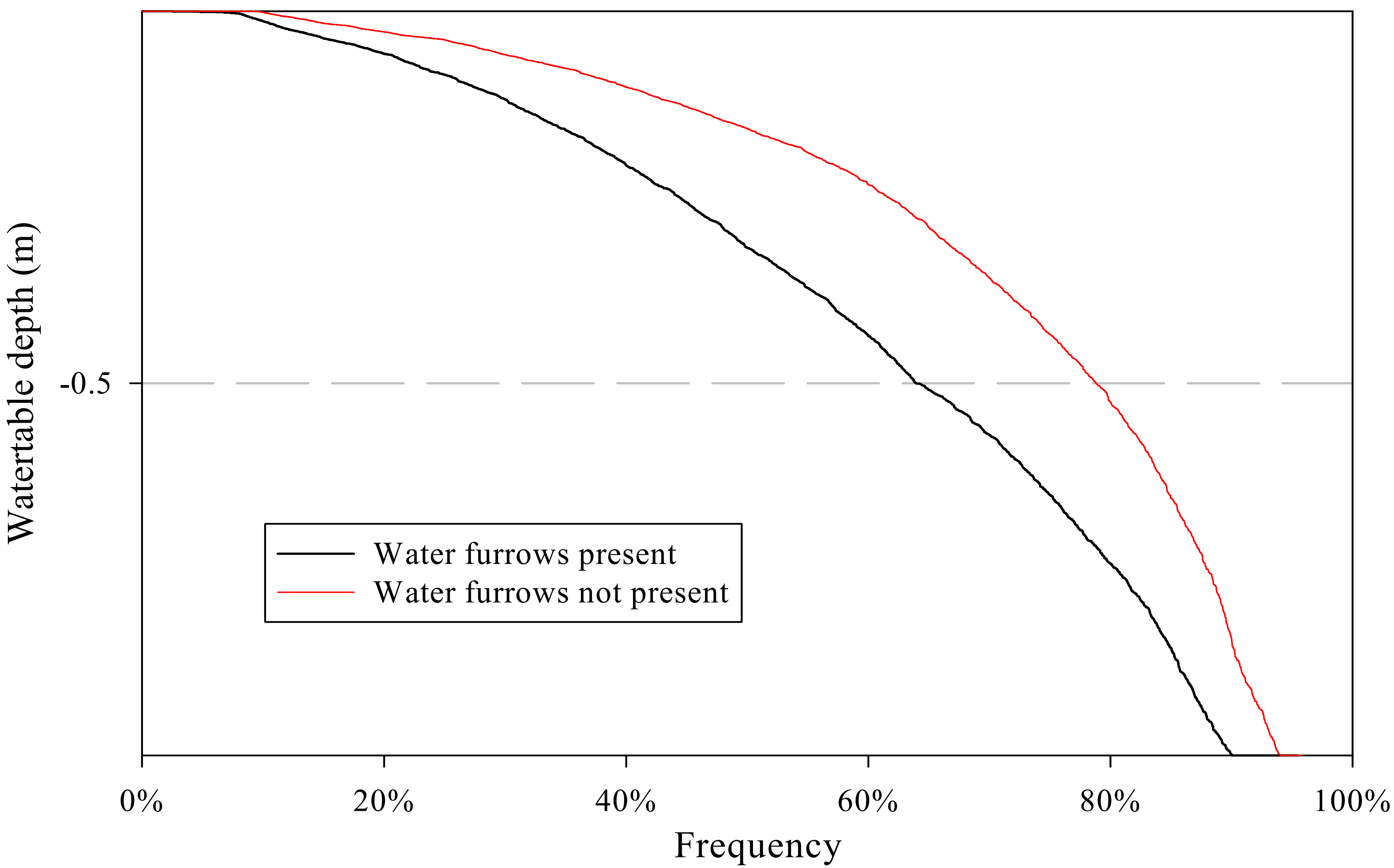


Figure 6.6 Comparison of the effect of water furrows on the frequency of the watertable depth

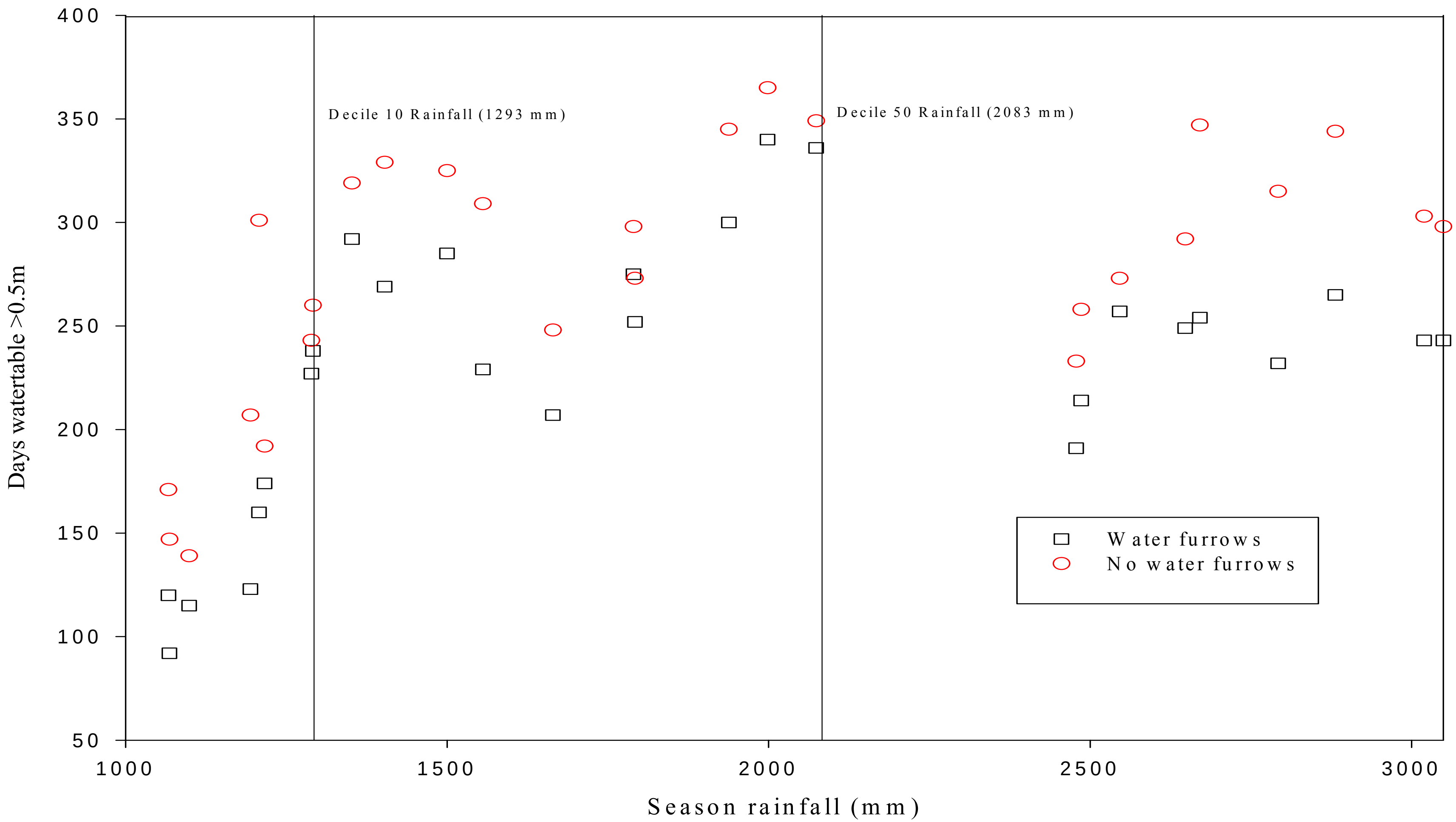


Figure 6.7 Average number of days that the simulated watertable was above 0.5 m as predicted by long term annual rainfall (BoM 2000). Vertical lines show the 10% and 50% chances of total annual rainfall

6.5.2.1 Number of days with shallow watertables.

The model was run over the nine years of weather record (1991-2000) for two water furrow spacings (Fig 6.5). A notable result is the probable persistence of the watertable over the nine years. Only on a few occasions does the model show no watertable present (Fig 6.5). The two simulated field designs (no water furrow and water furrow) showed similar responses, rapid rises in response to rainfall, followed by a slow decline. In general, the watertable was very dynamic through the nine year period with frequent rises and falls.

The simulation shows no flooding of the soil surface. This was an artefact of the modelling such that when the predicted watertable response was higher than the soil surface the simulated watertable height was reset to the soil surface (Section 5.3.2.3).

The hydrographs show that the overall watertable responses for both field designs are quite similar (Fig 6.5). There are some obvious differences in that the simulation of no water furrows show consistently higher watertable response than the simulation with water furrows (Fig 6.5). When water furrows were included in the design, the watertable dropped slightly more quickly and to a deeper depth than the design without water furrows; both simulated watertables responded to rainfall with rapid rises. Although there is a period from July to December 1992 when the watertable was either not present or was very low. This period corresponds to a very dry period when only 265 mm of rain fell, compared to the long term average of 450 mm for the same period. A similar dry period during the middle of 1999 and it also affected the simulated watertable response (Figure 6.6). There were many periods during the nine years that the simulated watertable remained above 0.5 m. The longest protracted period of waterlogging can be seen between January 1993 and March 1995. During this period the modelling suggested that the watertable in the field with no water furrows never fell below 0.5 m. The watertable in the field with water furrows did drop below 0.5 m on four occasions, however, it did not remain below 0.5 m for long.

The frequency of occurrence the watertable at specific depths over the wet season was calculated by determining the cumulative time the watertable exceeded known depths. This calculation was performed in Microsoft Excel using the frequency function.

The cumulative frequency of the watertable over the nine years of the simulation was plotted against the simulated watertable depths. The frequency of the simulated watertable for the field with the water furrow present was lower than that for the field without water furrows (Fig 6.7). The watertable was higher than 0.5 m for 64% and 79% of the time for a field with or with out water furrows, respectively (Fig 6.6).

6.5.2.2 Watertable response to growing season rainfall

The number of days that the simulated watertable was shallower than 0.5 m was plotted against the annual rainfall (Fig 6.7). The data reveal that there is a critical rainfall total above which there is no increase in the number of days the watertable is higher than 0.5 m for either field design.

There was little increase in the number of days the simulated watertable is lay shallower than 0.5 m when the rainfall total was about 1400 mm for both treatments, a figure that is well below the long term annual median for Ingham of 2084 mm (Fig 6.7, Table 6.5). The critical rainfall total for both field designs was about 1400 mm, after this there was very small increase to the number of days the watertable is above 0.5 m.

For the no water furrow design field, 1400 mm of annual rainfall represents about 300 days when the simulated watertable is lay shallower than 0.5 m while, the corresponding figure for the field with water furrows is about 250 days.

Table 6.5 Growing season rainfall and number of days of waterlogging

Year	Growing season rainfall (mm)	Average no of days watertable was above 0.5 m	
		Water furrows present	No water furrows
91-92	1067	115	151
92-93	1216	236	250
95-96	1291	195	273
94-95	1403	277	320
96-97	1665	252	275
93-94	2074	337	358
97-98	2546	246	292
98-99	2881	236	306
99-00	3019	230	288

6.5.2.3 Watertable response to wet season rainfall

The simulated wet season watertable response between December and April when plotted against the wet season rainfall revealed a similar pattern as that plotted against the annual rainfall (compare Figs 6.7 6.8). The number of days the watertable was above 0.5 m reached a constant plane and from that point on it was independent of rainfall. This point was about 1100 mm of wet season rainfall, for the field with water furrows and about 1300 mm for the field with water furrows.

A linear function was again fitted to the simulated data. The fitted function did not fit particularly well as judged by the adjusted r^2 53% with water furrows and 46% without water furrows (Appendix A3.3). but the function is useful to predict the trend of watertable response to wet season rainfall. The fitted function shows the number of days that the watertable was above 0.5 m would increase by one day for every extra 50 mm of wet season rainfall in field without water furrows and by one day for every extra 33 mm of wet season rainfall with water furrows (Fig 6.8). The reason the watertable responded quicker in the field with water furrows is due to the fact that there is only a finite number of days the field is waterlogged during the wet season and after that limit is reached the linear relationship of Fig 6.8 will break down.

The long term median wet season rainfall (BoM 2000) was plotted on Fig 6.8 and shows that under such rainfall, a field with water furrows would be waterlogged for 106 days during the wet season, while a field without water furrows would be waterlogged for 115 days.

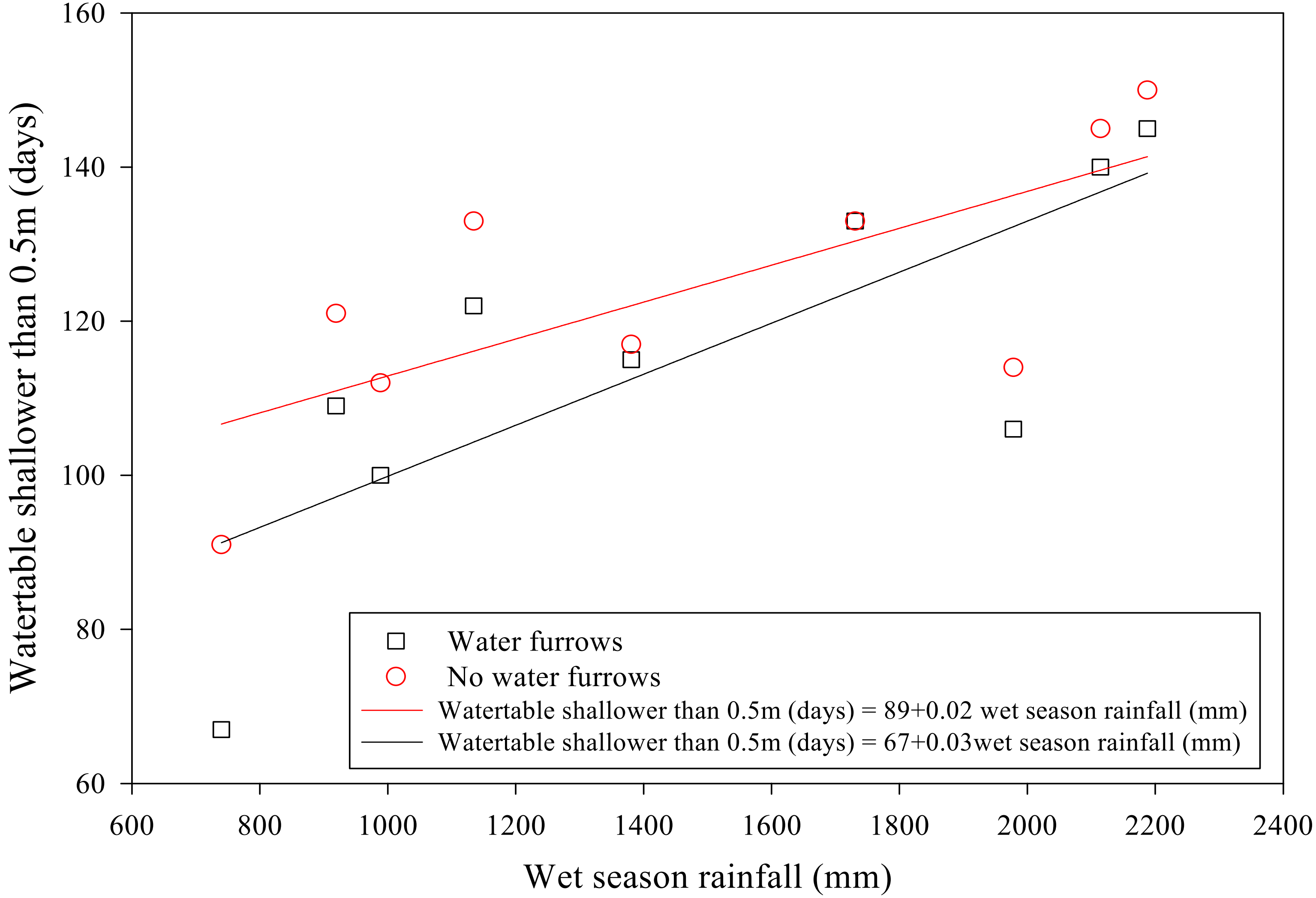


Figure 6.8 Number of days of the watertable was above 0.5 m as predicted by the wet season rainfall show as table

6.5.2.4 First 130 days watertable response to rainfall

The simulated watertable data for the first 130 days after planting or harvest was plotted against the rainfall totals from the same period. The simulated watertable responses, from the field with water furrows, for the three plant and harvest dates are shown in Figure 6.9. The median rainfall calculated from long term records (BoM 2000) was calculated to estimate the risk associated with each planting or harvest date. A linear function was fitted to the data with an adjusted r^2 of 0.95 for the curve through the watertable response from the field with water furrows and an adjusted r^2 0.93 for the field without water furrows (Appendix A3.4).

The simulated data shows that the early planted (July) or harvested sugarcane would experience less waterlogging in the sensitive 130 day period after planting or harvest, than the sugarcane planted or harvested after this date (Fig 6.9). The simulated watertable response from a field without water furrows was very similar to the simulated watertable response from the field with the water furrows. The closer the planting or harvest date was to the wet season the number of days of waterlogging increased.

The median rainfall line for September plant/harvest plotted on Fig 6.10 shows that there is a 50% chance of receiving 494 mm of rainfall in the 130 days after planting or harvest. If the 494 mm of rainfall did fall in that period, then a field without water furrows would be waterlogged for 50 days out of the 130 days or 38% of the time. A field with water furrows would be waterlogged for 70 days out of the 130 days or 53% of the time. However if the sugarcane was planted or harvested in November and median wet season rainfall did occur, then that rainfall would cause the watertables to exceed 0.5 m for about 85 days out of the 130 days or 65% of the time for the field with water furrows compared to about 100 days or 77% of the time for the field without water furrows (Fig 6.9).

The linear relationship suggests that for a field (with or without) water furrows would experience between 4 to 6 extra days of waterlogging for every extra 100 mm of rainfall within the 130 day period after planting or harvest. A field without water furrows would experienced more days of waterlogging than a field with water furrows under the same amount of rain.

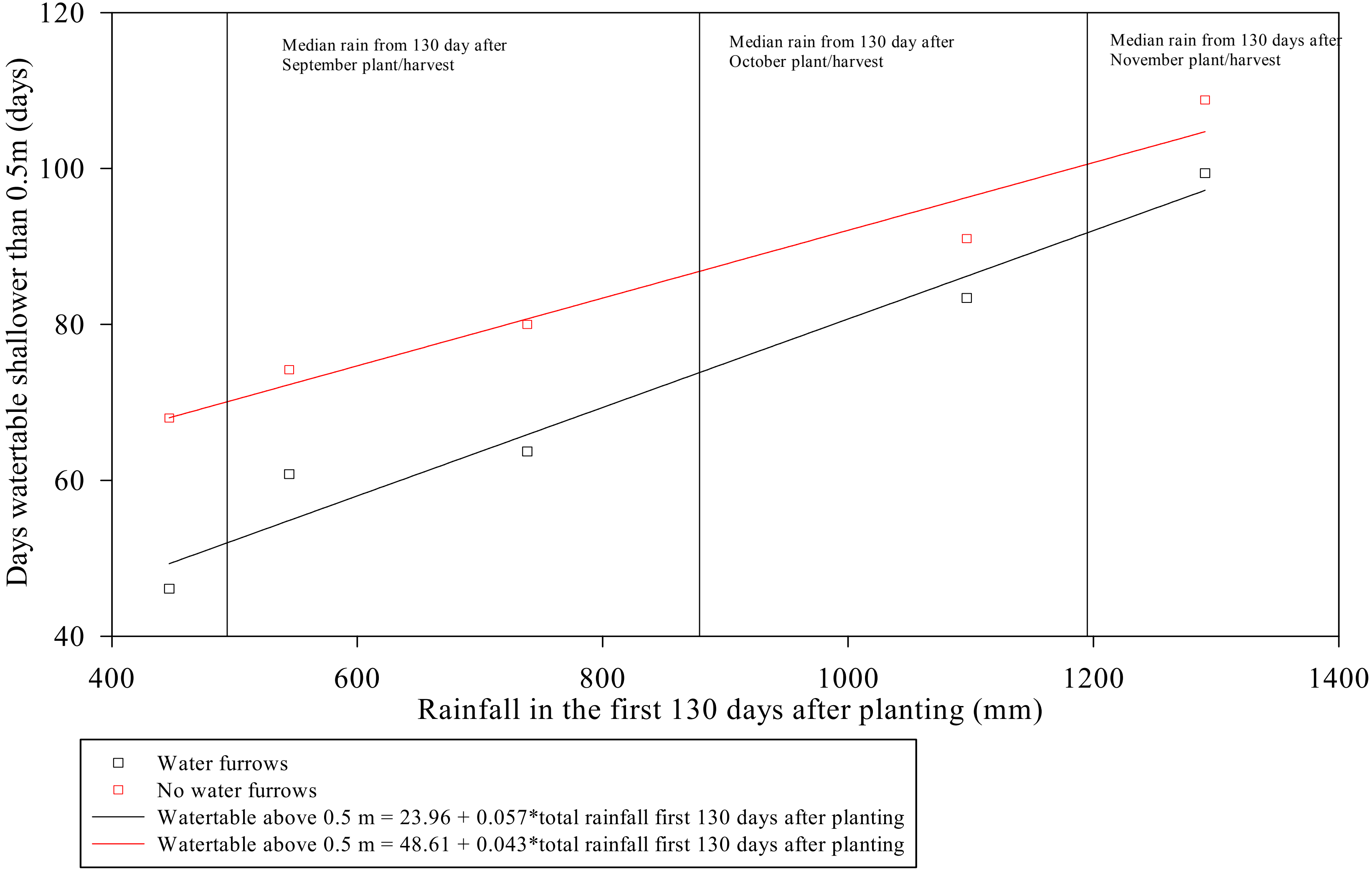


Figure 6.9 Number of days the watertable was above 0.5 m as predicted by rainfall in the first 130 days after plant/harvest.

6.5.2.5 Waterlogging tolerance

The tolerance of sugarcane to waterlogging was simulated by high crop coefficients and a planting date in September to show how such a crop may affect the watertable response. The watertable was higher than 0.5 m for 61% and 70% of the time for a field with and with out water furrows respectively (Fig 6.10).

The higher tolerance of such sugarcane varieties to waterlogging and subsequent increase in water extraction had a similar effect on waterlogging as the inclusion of water furrows in the field design (Fig 6.10). The total number of days the watertable was above 0.5 m in a field without water furrows and growing waterlogging tolerant sugarcane was similar for a field with water furrows and growing waterlogging susceptible sugarcane (Fig 6.10).

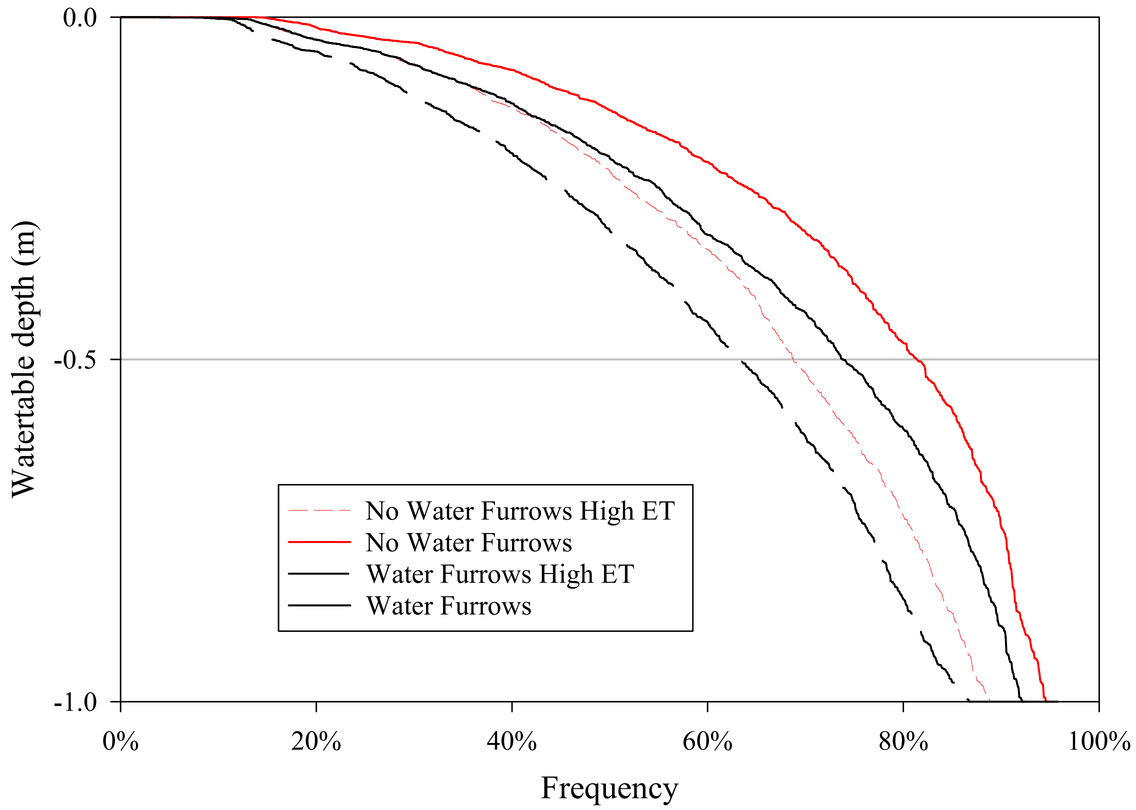


Figure 6.10 Comparison of the effect of water furrows and waterlogging tolerant sugarcane (high ET) on the frequency of the watertable was between the surface of the soil and 1.0 m deep.

6.5.2.6 Mounding

Mounding of the sugarcane rows produced a noticeable decrease in the number of days the sugarcane was exposed to watertables above 0.5 m (Fig 6.11). However the data reveals that mounding alone was less effective than the inclusion of water furrows. The field with water furrows and not mounded experienced fewer days of waterlogging than a non water furrowed field that was mounded (Fig 6.11).

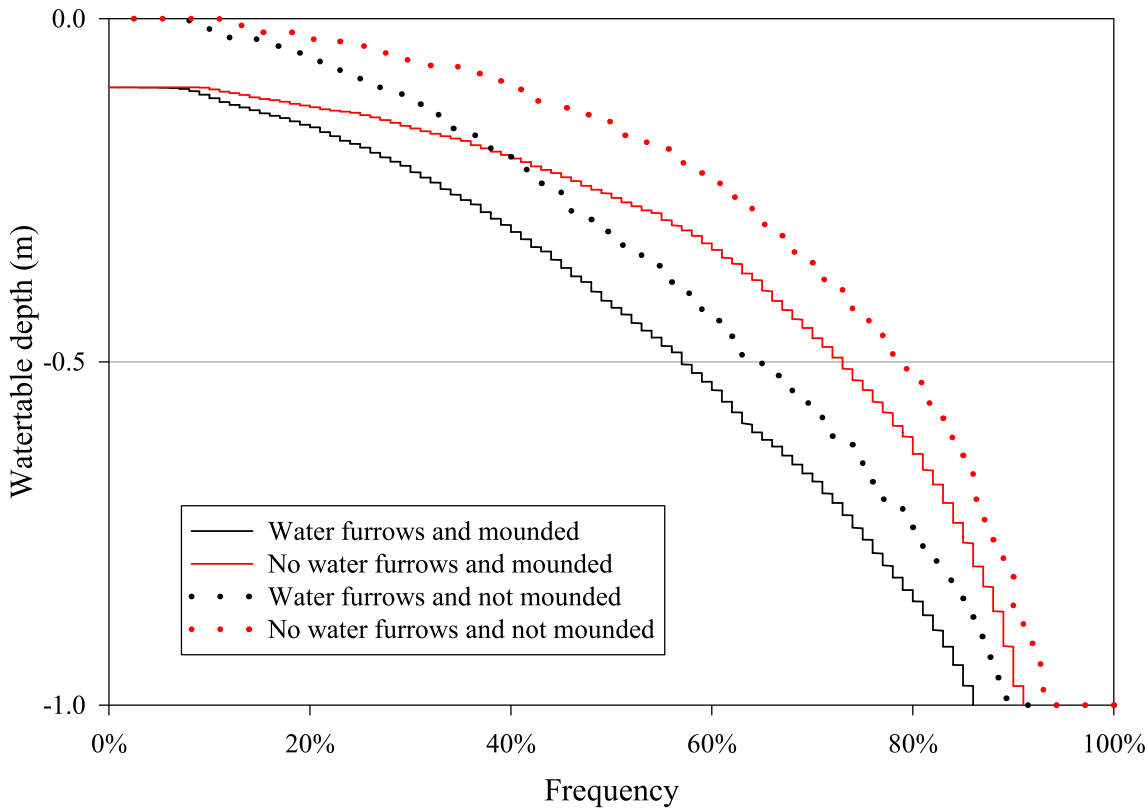


Figure 6.11 Comparison of the effect of water furrows and mounding on the frequency of the watertable was between the surface of the soil and 1.0 m deep.

6.5.2.7 Sugarcane yield models

The results from the watertable model were used to predict the potential yield reduction in sugarcane from the yield models Gayle *et al*. (1987) and Rudd and Chardon (1977).

- ***Rudd and Chardon (1977) model***

The Rudd and Chardon model does not account for when the sugarcane is planting or harvesting. The modelling presented below reveals that the assumptions of timing of waterlogging within the growth cycle of the sugarcane plant are too broad to be of any real use.

The sugarcane yield model of Rudd and Chardon (1977) is expressed in the terms of relative yield. The maximum potential yield for the Lower Herbert Valley was taken as 165 t/ha (Murchow *et al.* 1995). The modelling shows that the potential yield due to the presence of watertables above 0.5 m is insensitive to plant/harvest date (Fig 6.12). The presence of water furrows increased the calculated yield reduction, as compared to sugarcane yields calculated in fields without water furrows. This is due to the fact that removing the water furrows increases the productive area by about 15%. In actual terms an extra row of cane can be grown for every 14-16 rows of the field. When this is taken into account, the increase in yield more than compensates for the losses incurred by the increased waterlogging.

The potential yield from all plant dates for fields with water furrows is 53% while from fields without water furrows it is 55% (Fig 6.12). The yield reduction calculated from the Rudd and Chardon (1977) model confirms the previous results that water furrows have a small effect on the yield potential.

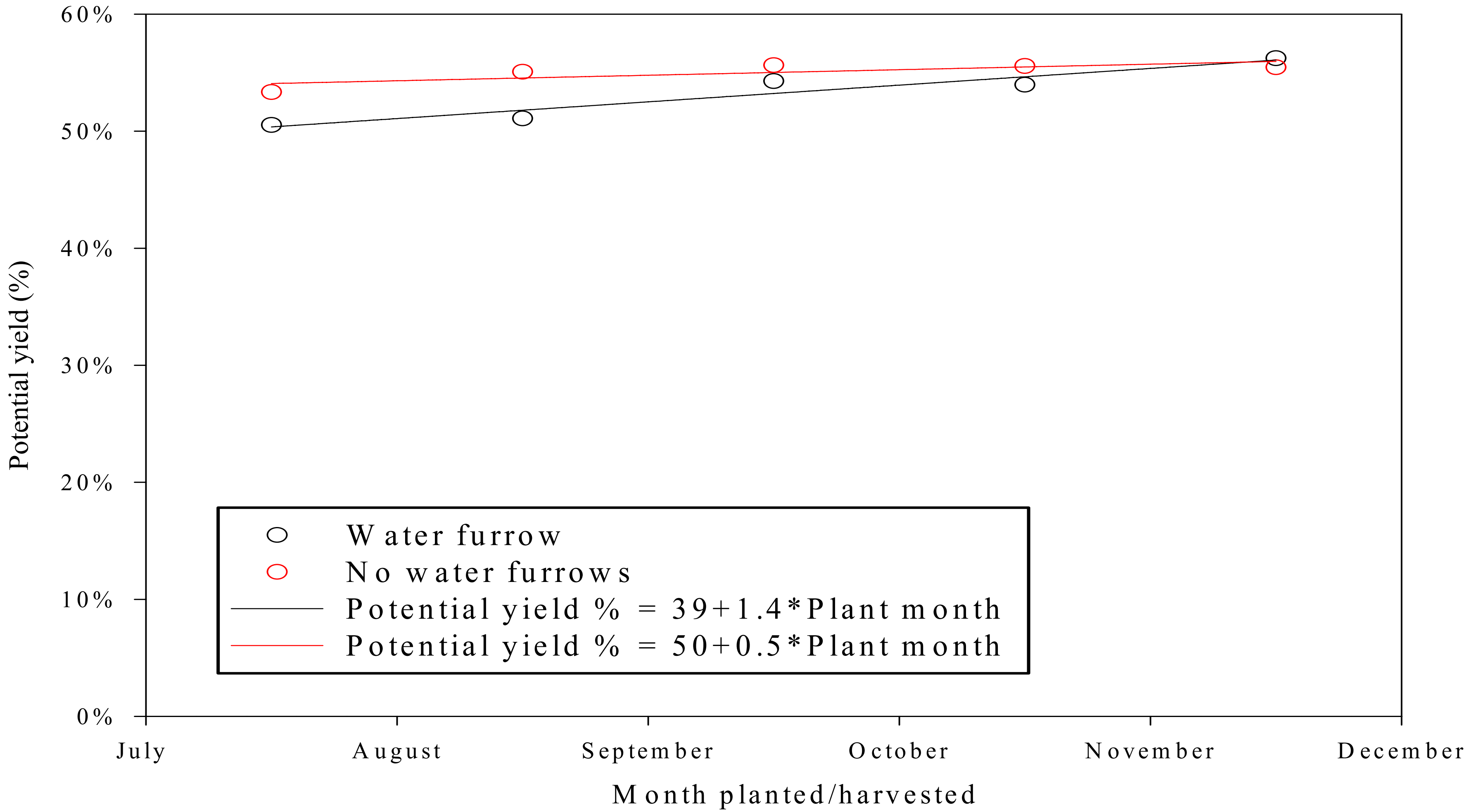


Figure 6.12 Sugarcane yield reduction calculated from the Rudd and Chardon (1977) model, usimg simulated watertable responses with and without water furrows and different planting or harvest dates.

6.5.2.8 Plant/Harvest date

The yield potential calculated for the different plant/harvest dates shows that the yield reduction calculated by the Rudd and Chardon (1977) yield model is insensitive to plant or harvest date. The modelling reveals that there is little effect on yield caused by different plant/harvest dates. This is due to the way this model calculates the yield loss. The Rudd and Chardon model assumes that there is a 0.46 t/ha decrease in yield for every day the watertable is above 0.5 m between December and June (Rudd and Chardon 1977). However it is known that sugarcane is more sensitive to waterlogging during the early growth stage (Section 1.2.8). The results suggest that this model is not suited to compare simulated yields of waterlogged sugarcane from different plant/harvest dates.

A linear function was fitted to the calculated sugarcane yield potential when grown in fields with water furrows with an r^2 of 87% while the function fitted to the calculated sugarcane yield potential when grown in fields without water furrows had an r^2 of 78% (Fig 6.12 Appendix A3.5). The very low slopes of both the fitted functions indicate the relative insensitivity of yield potential to plant /harvest date. There is a slight increase in yield potential if the crop is planted or harvested in November (Fig. 6.13). However this model does not account for the growth stages in the plant that may be more sensitive to waterlogging.

- ***Gayle model***

The Gayle *et al.* (1987) model calculated the percentage of potential yield, and revealed that shallow high fluctuating watertables decrease the yield of sugarcane (Fig 6.13).

The Gayle *et al.* (1987) model predicted the potential yield of sugarcane for the field with water furrows to be 19% higher than that of planted or harvested on the same date in a field without water furrows (Fig 6.13). The difference between field designs was relatively constant over the different planting or harvesting dates (Fig 6.13).

The yield of sugarcane calculated by the Gayle *et al.* (1987) model shows that the closer planting or harvesting is to the wet season, the lower the potential yield of the subsequent sugarcane crop (Fig 6.13). The effect of planting or harvesting date outweighed the influence of the water furrows on potential yield. There is between a 22% to 26% increase in potential yield of sugarcane if the plant or harvest date is in July as compared to November. This compares favourably with a 10% increase in potential yield from removing water furrows. There was a greater response to change in a management practice (planting or harvesting date) than there is to a redesign of the field.

A linear regression was fitted through the calculated sugarcane yield potential data when grown in fields with water furrows with an adjusted r^2 of 0.88 (Fig 6.13). The slope of the regression line of 5.4% indicates that for every week the sugarcane is not planted or harvested there is a potential yield decline of 5.4% for fields with water furrows and of 6.7% with a adjusted r^2 of 0.99 for those without water furrows.

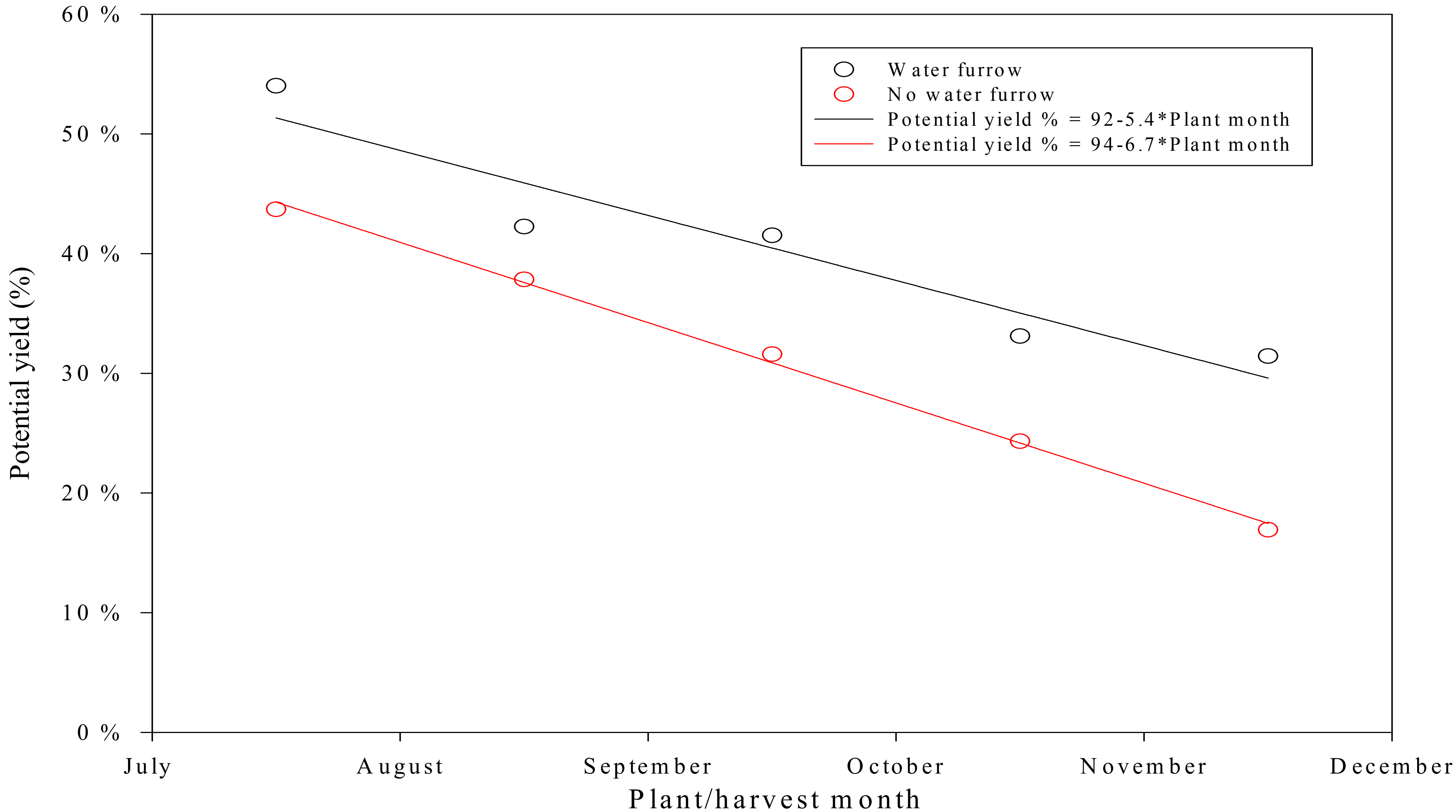


Figure 6.13 The potential sugarcane yield calculated from the Gayle *et al.* (1987) model, from simulated watertable response with and without water furrows and different plant or harvest date

6.6 SURFACE DRAINAGE CRITERIA FOR LOW LYING SUGARCANE FIELDS

The results from the scenario modelling have led to a formulation of the following criteria for surface drainage of low lying sugarcane fields.

6.6.1 Inundation

The modelled peak flow rates and the calculated recession coefficient reveals that the field design characteristics to affect the duration of inundation are combinations of trash management, field slope, and field length.

The field design criteria for inundation from a sugarcane productivity point of view is to remove excess rainfall from the fields before there is any detrimental effect on yield. From a catchment point of view, however the removal of runoff from the fields should not affect fields further down the catchment. It is important to balance productivity with management of the catchment wide drainage problems. The current field design allows high rates of runoff to discharge and fill the drainage system, and the surface water balance shows that on average 60% of the measured runoff is discharged through water furrow (Section 3.4.3). Water furrows have been shown to have little influence on the shallow fluctuating watertables (Section 6.5.2) and their role in the water balance is to greatly increase the field response to rainfall (Section 3.4). Hence the objective is to design a field that will have a lower response to rainfall than the current design. Removal of water furrows from the field design will reduce the peak runoff rates by increasing the hydraulic resistance of the land and removal of a preferential runoff pathway. Hence it is recommended that water furrows not be used in the field design in order to minimise the impact of the field drainage throughout the catchment.

The current inundation criterion is to remove 85% of the water from sugarcane fields within three days after a three day, three year, return rainfall event (Gutteridge Haskins and Davey 1976). The length of inundation modelled above reveals that, on average, the water would drain from the fields between 6 to 8 hours from the initiation of runoff (Section 6.5.1).

Removal of the trash blanket, although highly undesirable due to other cultural factors (Section 2.2.1), appears to be the easiest management option to implement to increase the speed of drainage waters of the fields. The removal of the trash blanket greatly increases the peak flow rates in the shorter, steeper fields (Tables 6.1, 6.2). It is not desirable to increase the peak flow rate from the fields to the regional drainage system as the regional drainage system at this point is already overfull. The calculated recession coefficient for the scenarios modelled above showed that none of the modelled scenarios were not inundated for more than 36 hours (Table 6.3). This figure is well below the critical 72 hours identified in the current design criteria. It should be noted that this result is for an idealised field that has no restricted drainage. As discussed previously (Section 3.4), the flow regime from fields is complex with the regional drainage system restricting the drainage water from the field and increasing the time that water inundates the field. The scenarios modelled showed that water drains from the field well before the critical 3 days, therefore retaining the trash blanket is recommended.

The effect of slope on peak flow rates and the recession coefficients revealed that high flow rates would occur at the steeper slopes (Section 6.5.1). The recession coefficients in the flatter slopes were again well below the 3 day critical limit, however field slopes that are flatter than 0.01% may be affected by inundation. It is recommended that the field slopes should be no flatter than 0.01%. The recommendation for the upper range of field slopes should revolve around retaining water on the field to minimise the risk of inundation downstream. To minimise any effect of high rates of water draining into the regional drainage system the range of slopes should be within the range 0.01 to 0.125%.

The length of the field also affected peak flow rates and the recession coefficients. The longer the field lengths, the lower the peak flow rate, and the higher the recession coefficients (Section 6.5.1.5). Again, the recession coefficient was well within the critical 3 day limit however the longer the field, the higher the risk of inundation occurring (Section 6.5.1.6). The shorter the field length, the higher the peak flow rates and with an increased risk of downstream flooding if field lengths are too short (section 6.5.1.6). An optimum field length appears to be between 300 m and 600 m. This range would minimise the risk of inundation and, at the same time, reduce the risk of exacerbating the downstream flooding by increasing the drainage water flow to the regional drainage system.

Research so far has been focused on the field response to rainfall without consideration of the location of the field's position in the drainage catchment. Although the present study did not attempt to model the effect the flow of the drainage system on field discharge, the recommended criteria should be viewed as those for an idealised field where drainage is unimpeded by the regional drainage system. The current field design has an advantage of being able to remove excess rainfall from the field very rapidly. Therefore, when applying the surface drainage criteria over the catchment, there must be some allowance for the position of the field in the catchment. It may be possible to encourage the growers in the upper part of the catchment to remove water furrows, while growers in the lower portion might retain water furrows, to facilitate the quicker drainage in the lower parts, but continuing at a lower rate in the higher parts of the catchment. To ease the small production loss by removal of water furrows the growers in the upper catchment area might then be given priority for an early planting or harvesting date which would compensate for the small yield decline due to the extra waterlogging.

In summary the optimum field design to combat inundation and minimise the risk of downstream flooding would be a field without water furrows, with a trash blanket present, and a field length of between 300 and 600m, and a slope between 0.12% and 0.01%.

6.6.2 Watertable criteria

The field design parameters that influence sugarcane yield by either affecting the shallow fluctuating watertable or affecting the plant directly were the presence of water furrows, the date of planting or harvest, mounding of the sugarcane rows, and increasing the tolerance of sugarcane to waterlogging.

None of the field designs or the use of waterlogging tolerant sugarcane completely removed the occurrence of shallow fluctuating watertables. Therefore, the influence of such a watertable on sugarcane production must be minimized in the new optimized drainage criteria. The aim of the new criteria will be to minimise the time that the shallow, fluctuating watertable are shallow than 0.5 m in the period that the sugarcane is most sensitive to waterlogging. This period is not well defined and the current understanding is that the plant is most sensitive to high watertables during 130 days after planting or harvest (Section 1.2.8).

The modelling showed that on average a watertable was present in the field (irrespective of design) for 69% of the time and caused a 50% reduction in the potential yield.

The removal of water furrows from the field design would have only a small influence on the dynamics of the watertable (Section 6.5.2.1). This was reflected in the amount of time the watertable was above 0.5 m throughout the growing season. Fields with water furrows were waterlogged for 64% of the time as compared to fields without water furrows being waterlogged for 79% of the time (Section 6.5.2). The greater number of days waterlogged can be attributed to the amount of water removed from the watertable as interflow (Section 4.4.2.5). The analysis of the watertable dynamics indicates that water furrows are effective in controlling the shallow fluctuating watertable (Section 6.5.2.1). However this has to be explored in terms of the timing of the effect and whether the effect is when the sugarcane is sensitive to a high watertable.

The presence of water furrows decreases the number of days that the field would be waterlogged during the wet season under median rainfall from 115 days to 106 days (Section 6.5.2.3). The trend indicates that the higher the wet season rainfall, the more likely the chance that the field will be waterlogged. For sugarcane planted later in the year this period would coincide with the critical 130 day period (Section 6.5.2.3).

The number of days the watertable is higher than 0.5 m in the 130 day period after planting or harvest shows the increased risk associated with planting or harvest operations closer to the onset of the wet season (Section 6.5.2.4). The simulation results showed that for a field with water furrows planted or harvested in July, the number of days the field may experience waterlogged conditions would be 45 days as compared to 70 days a field without water furrows (Fig 6.10). This difference of 25 days narrows as the planting or harvest date approaches the wet season. The difference in the number of days of waterlogging between fields with and without water furrows for the September plant/harvest is about 20 days while the figure for the November plant/harvest date is 10 days (Fig 6.10).

The Gayle *et al.* (1987) model showed:

1) there was a small effect on yield (5%) between the fields with water furrows and those without water furrows,

2) there is a higher probability of decreasing sugarcane yields the closer the crop is planted or harvested to the wet season, and,

3) defined a period of 130 days after planting or harvest that is more sensitive to waterlogging than the other parts of the sugarcane growth cycle.

The model predicts an increasing chance of decreased yields the closer the planting or harvest date is to the wet season. This risk is expressed as for every week that sugarcane planting or harvesting is delayed after July, yield will decline by 5.4% if the field has water furrows and 5.9% if the field does not have water furrows (Section 6.5.2.4).

Modelling of the crop response to waterlogging tolerant sugarcane varieties (6.5.2.5), simulated by a high crop coefficients, suggest that there may be merit in breeding sugarcane for waterlogging tolerance. The amount of time the watertable was shallower than 0.5 m was reduced from 115 days of the wet season with the current sugarcane varieties to 99 days of the wet season with the waterlogging tolerant varieties.

Mounding of the sugarcane rows were less effective in combating simulated waterlogging than the presence of water furrows (Section 6.5.2.6). The data suggests that sugarcane grown on mounds in fields without water furrows would experience more days of waterlogging than sugarcane grown flat in field with water furrows (Section 6.5.2.6).

Field design criteria to minimise the risk of waterlogging should include some mechanisms to decrease the chance of watertables exceeding 0.5 m. The modelling in Section 6.5.1 revealed that water furrows play a small role in controlling the dynamics of the watertable. The effect of water furrows on waterlogging is quite small in comparison to the overall effect of waterlogging on the yield of sugarcane. Removal of water furrows would increase the effective production area by about 15% and this increase in production would compensate for the increased waterlogging experienced in fields without water furrows. For this reason and the reasons outlined in Section 6.5.1 it is recommended that water furrows be removed from the field design. Mounding decreases the number of days of waterlogging compared to that under non mounded sugarcane, and this could possibly be a compromise solution between removing water furrows in the field design and including water furrows.

CHAPTER 7 SUMMARY AND FUTURE RESEARCH DIRECTIONS

This thesis has attempted to develop guidelines to overcome waterlogging and inundation in the Lower Herbert Valley through the development of optimal design criteria for low lying sugarcane fields. Initially little was known about the basic hydrological response of these fields to rainfall and the thesis has filled some of that gap. To develop effective drainage design criteria the response of sugarcane to excess water must be known. This understanding of the plant's response to excess water is a focus of another study (Burry 2001) and deeper understanding of the responses may be still some time away.

Empirical relationships between sugarcane yield reduction and number of days waterlogged have been used, but these relationships do not shed any light on the biological mechanisms that causes the reduction in yield. The literature shows potential areas of research such as the reduction oxidation potential of the soil, and the dissolved oxidation level in the soil water (Carter 1980; Bury 2003). The measurement of the watertable level is possibly an integration of all the associated biophysical response and hence may be why the published relationships (Gayle *et al.*; Rudd and Chardon 1977) have such good predictive value. It must be a area of further research to fully understand the mechanisms.

7.1 SUMMARY OF FINDINGS

The surface hydrological characteristics of three low lying sugarcane fields were measured and it was found that the regional drainage system controlled the runoff from the fields (Section 3.4). The runoff from the fields was mainly submerged flow with free flow occurring only at the very beginning and at the very end of the runoff event (Section 3.4).

The use of simple height stage recorders, such as flumes or weirs, to measure discharge rates is not appropriate in environments such as the Lower Herbert Valley (Section 3.4). Low relief slopes and non-integrated drainage design, coupled with high intensity and high volumes of rainfall restricts the free movement of water from low lying fields (Section 3.4).

It was also found that, contrary to expectations, inundation of sugarcane fields was not a major cause of yield loss (Section 5.4). The recession time for the measured runoff events was between 1.2 and 7.6 hours, well below the critical 72 hours as required for yield loss (Section 3.4).

The Manning's equation provided a robust relationship for the description of overland flow through a sugarcane trash blanket (Section 3.4), while the generic depth-discharge equation proposed by Turner and Chanmeesri (1984) fitted the observed data well (Section 3.4.1) but was not used in any predictive capacity. The depth-discharge equation parameters in general agreed with the proposition of Maheshwari (1992) that the exponent of the depth discharge relationship indicates the type of flow regime (Section 3.4; Table 3.4). The exponent for the flow (α_f) on the low slope with trash blanket was 2.66 which may equate to a mixture of both turbulent and laminar flow (Maheshwari 1992). The exponent of 2.06 for the flow through trash on higher slopes indicates a mixture of both turbulent and laminar flow (Section 3.4). When the trash was removed, the flow became more turbulent and the exponent measured was 1.67, which agrees with the value suggested by Maheshwari (1992) (Section 3.4).

The surface water balance of the Main Palmas site field shows that the water furrow acts as a preferential pathway for runoff (Section 3.4.1; Table 3.12). The surface water balance revealed that, on average, only 36% of the runoff from the field exits by the rows. The water furrow allows high volumes and rates of water to enter the drainage system quickly (Section 3.4.1; Table 3.12). Although the area of rows is about 87% of the total field area, the remainder is water furrows but only 38% of the runoff leaves via the rows. The majority of the runoff (64%) leaves the field via water furrows (Section 3.4.1; Table 3.12).

Waterlogging of sugarcane in the heavy textured far levee soils, such as those at the Palmas Site, is caused by the low saturated hydraulic conductivity of the lower soil horizons (Section 4.4) located below 1 m deep and have saturated hydraulic conductivities of less than 0.8 mm/hr (Section 4.4; Table 4.6). Combined with the low specific yield of the soil it requires only 100 mm of rain to completely saturate the uppermost 1 m of the soil.

The Palmas site was waterlogged, as defined by Rudd and Chardon (1977), for most of the study period (Figure 4.9; Section 4.4). The watertable was very dynamic with rapid rises after rainfall followed by slow declines (Section 4.4; Figure 4.9). As water was removed from the watertable by evapotranspiration, deep drainage, and interflow, the watertable declined (Section 4.4; Table 4.8). The dominant process that caused this decline was evapotranspiration (Section 4.4). Evapotranspiration and surface runoff were the significant terms in the water balance (Section 4.4; Table 4.11). Deep drainage contributed more to the water balance than interflow (Section 4.4; Table 4.8).

Point measurements of watertable responses such as individual shallow wells at the Palmas Site, provided good spatial representations of the watertable present in the field (Section 4.4; Figure 4.14).

Sugarcane yields were affected by the presence of shallow watertables (Section 4.4.4). Only in 1997-98 was the sugarcane yield close to the long term average yield. This was the only year that the sugarcane yield from the Palmas Site was higher than the district average, in the other wetter years of the present study the yields at the Palmas Site were below the district sugarcane yield average and well below the long-term district sugarcane yield average. The sugarcane yield components of the 1998-99 crop revealed a strong declining trend across the field bed that was closely related to the depth of the watertable. The rows in the middle of the bed (row 7) had more stalks and were much heavier than the stalks closer to the water furrow in rows 1 and 3 (Section 4.4; Table 4.10).

It was found that the drainage system behaved in such a way that the flow in the large field flume could be simulated by assuming the water flow from the sugarcane field was being restricted by a high resistance to flow (i.e. high Manning's n). This assumption was tested over two wet seasons and it was found that SWMM (Huber and Dickenson 1995) could be used to simulate the dynamics of runoff from the field, especially when a value of 0.1 was used for Manning;'s n in the presence of a trash blanket (Figure 5.3).

The watertable model of Youngs *et al.* (1989) simulated the dynamics in the field of the shallow fluctuating watertable over a period of 2 years of relatively high rainfall. The robustness of the measured soil hydraulic parameters was demonstrated by the model's simulation of the measured watertable data (Figure 5.7) as measured by the coefficient of determination (E = 0.59) and the index of agreement (d=0.86). The model predicted the shallower watertable responses better than deeper responses (Section 5.5.2), possibly as a consequence of a number of assumptions in the model.

Two sugarcane yield models proved to be good predictors of the biomass yield of sugarcane grown in soils with shallow fluctuating watertables. The Rudd and Chardon (1977) model was found to be an excellent predictor of yield of sugarcane under conditions of excess water. Raising the critical watertable depth in the Gayle *et al.* (1987) model from 0.45 m to 0.4 m below the soil surface also permitted it to be a reliable predictor of biomass yield of sugarcane. Both models are empirical models that require no understanding of how the reduction of yield occurs.

7.2 DRAINAGE CRITERIA

The current inundation criterion is to remove 85% of the water from sugarcane fields within three days after a three day, three year, return rainfall event **(**Gutteridge Haskins and Davey 1976). The duration of inundation modelled (Section 6.4) revealed that, on average, surface water would drain from the fields between 6 to 8 hours from the initiation of runoff (Section 6.5.1) when the field did not contain a water furrow.

The flow regime from the fields is complex with the regional drainage system restricting the drainage water from the field, and increasing the time that water inundates the field. All the scenarios modelled, slope, trash blanket, and length (Section 6.5) revealed that water drains from the field well before the critical 3 days required for sugarcane yield reduction. This finding has a number of ramifications;

- The effect of the trash blanket is to slow the removal of water from the fields. However as the drainage water is removed before 3 days of inundation that reduces sugarcane yields keeping the trash blanket is recommended.

- The upper range of field slopes should involve retaining water on the field to minimise the risk of inundation downstream. To minimise any effects of the high rates of water draining into the regional drainage system the range of field slopes should be within the range of 0.01 to 0.125%.

- An optimum field length appears to lie between 300 m and 600 m. This range would minimise the risk of inundation and at the same time reduce the risk of exacerbating the downstream flooding by increasing the drainage water flow to the regional drainage system.

Watertable modelling (Section 4.5) revealed that the presence of water furrows decreases the number of days that the field would be waterlogged during the wet season given median rainfall during that period would be from 115 days to 106 days. The long term modelling suggests that on average a watertable was present in low lying sugarcane fields (irrespective of design) for 69% of the time which caused a 50% reduction in the potential yield (Section 6.5). Simulation of removal of water furrows from the field design indicated only a small influence on the dynamics of the watertable therefore yields. However the removal of water furrows would allow additional areas previously occupied by the water furrows to be planted to sugarcane. The biggest effect on the sugarcane yields occurred when there was a September planting or harvest date. This scenario allowed the sugarcane to establish and regrow during the dry season and avoided waterlogging during the sensitive first 130 days after planting or harvest. Also management of the watertable is not possible with the current design of water furrows every 14-16 rows, due to the low amounts of water that is drained as interflow (Section 4.4). This leads to the following recommendations:

Water furrows be retained in fields in areas of high risk of inundation to minimise the effect of inundation.

Water furrows be removed from fields in other areas and the additional area be planted to sugarcane.

7.3 Knowledge gaps

At the beginning of the thesis (Section 1.3) the following questions were asked. They can now be answered by referring to the relevant sections in the thesis

- What field design criteria can be formulated that will decrease the likelihood of low lying fields being inundated? Section 7.2
- Does laser levelling of low lying fields reduce the risk of inundation? No Section 3.4
- How do water furrows affect runoff? Section 3.4
- What field design parameters in low lying fields are the most important in managing the runoff process? Section 7.2
- How does a trash blanket affect the generation of runoff from a low lying sugarcane field? Section 6.4
- What are the pathways of runoff from a low lying field? Section 3.4
- What field design criteria can be formulated to decrease the likelihood of low lying fields being waterlogged? Section 7.2
- What influence does the presence of water furrows have on the perched watertable within a low lying sugarcane field? Section 6.4
- What are the pathways for movement of groundwater in a low lying sugarcane field? Section 4.4.

- Can incorporation of improved drainage into field design increase the accessibility and timeliness of farming operations in a low lying field? This question remains unanswered by this thesis.

7.4 FUTURE CATCHMENT PLANNING

To minimise the effect of high flow rates exiting fields and flooding the regional drainage system and in turn flooding fields further downstream, it may be possible to encourage the growers in the upper part of the catchment to remove water furrows. Growers in the lower portion might retain the water furrows, to facilitate the quicker drainage in the lower parts but continuing at a slower rate in the higher parts of the catchment. To ease the small production loss by the removal of water furrows, the growers in the upper catchment area might then be given priority for an early harvest date which would compensate for the small yield decline due to the extra waterlogging.

A detailed soil survey of the lower Herbert valley exists, and could be combined with pedo-hydrological modelling approach (Timmer 1998) and the modelling framework presented in this present study, to assess the risk of inundation and waterlogging. The soils and areas of higher risk may allow the sugar mills or harvesting groups to harvest preferentially those areas. This would both increase the productivity and sustainability of the sugarcane industry in the lower Herbert Valley.

7.5 AREAS OF FURTHER RESEARCH

In recent years the sugar industry has funded research on a high density planting (HDP) system. The effect of this changed field design on the hydrology of the field is briefly explored.

7.5.1 Future field designs

The HDP system has raised beds 2m wide and 0.1m high in which 4 rows of cane grow and in between the rows are permanent tracks for field operations.

A high density field was simulated by HYDRUS-2D and a run over a 1 month period from 15 February 1999 to 15 March 1999. The data required for this was daily rainfall and daily evapotranspiration. This data was taken from the weather station located at the Palmas Site.

HYDRUS-2D requires soil physical parameters such as saturated hydraulic conductivity and soil moisture retention function. This data was taken from Section 4.4.

The geometry of the field was defined as being a raised bed 2.0 m wide and 0.2 m high. Half the width of the bed was simulated to reduce computation.

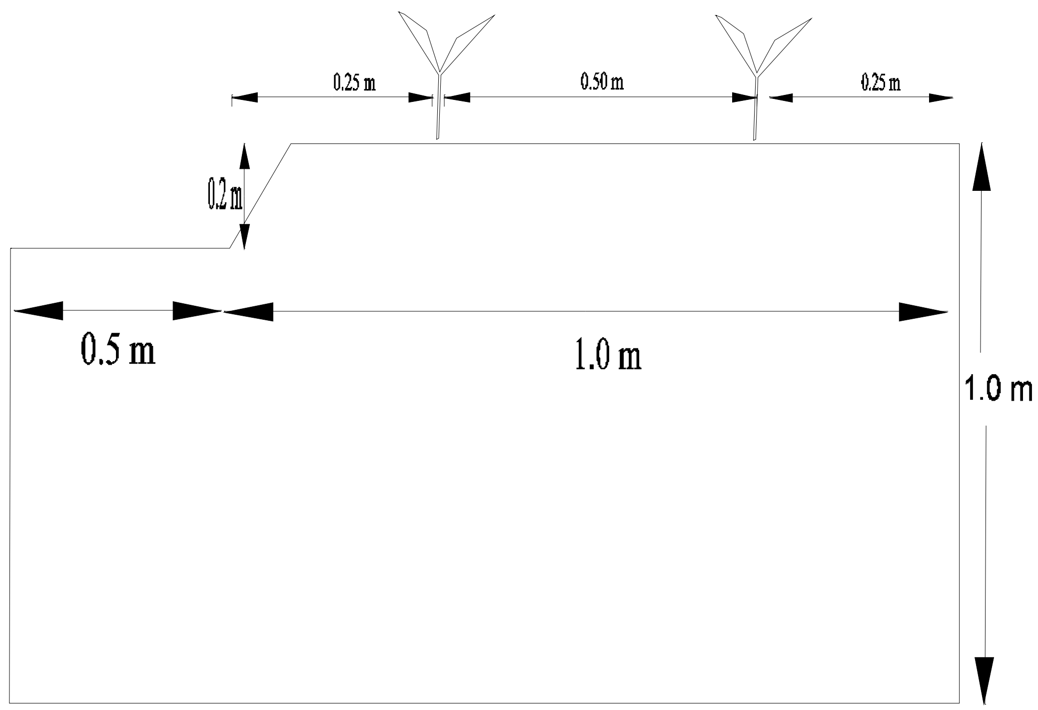


Figure 7.1 Cross section of the HDP bed use in HYDRUS-2D model

The watertable in the HDP field dropped at a faster rate and to a deeper depth as compared to the watertable under the conventional field design for the same amount of rainfall. There were still periods of waterlogging under the HDP design however the HDP design reduced the length and intensity of waterlogging. The days that the field was waterlogging were reduced from 27 days in the conventional field to 17 days for the HDP designed field.

From the limited modelling presented here HDP appears to offer an alternative design to combat waterlogging. The HDP modelling was experimental and it should be noted that this approach was coarse was used to scope out alternative field designs. The evapotranspiration from HDP crop geometry would need to be studied in more depth than that presented here. The model used in the present study, HYDRUS-2D was the only model available at the time that would simulate the movement of soil moisture in two dimensions. This model is complex (Section 4.2) and the internal algorithm can become unstable when solving a scenario that includes a seepage face with a saturated and an unsaturated zone (F. Cook, pers. comm.). For this reason only a 30 day period was simulated.

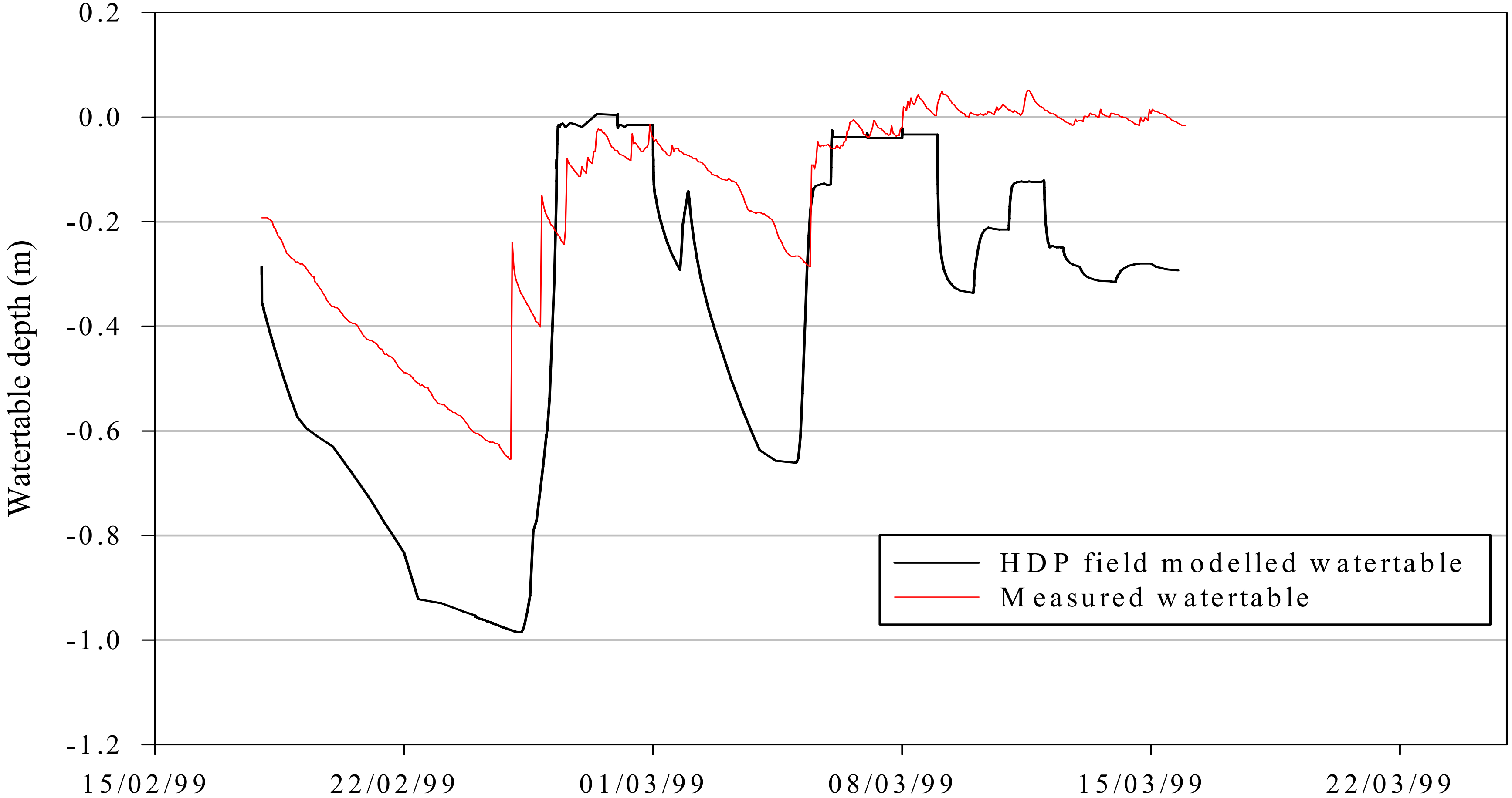


Figure 7.2 Modelled watertable response in a high density planting field compared to measured watertable response in a conventional field design

The current sugarcane farming system is centred on 1.5 m row spacings and all the farming equipment is designed to work with this design. The HDP design would mean that not only planters and harvesters have to change but also spray and cultivation equipment. However the move towards the HDP design with the raised centre bed would allow more flexible crop rotation options for the grower. The modelling above suggests that the raised HDP bed is waterlogged less than the traditional design which would allow the inclusion of legumes or other broadleaf break crops in the sugarcane farming system.

The HDP design may also allow better trafficability due to the permanent wheel tracks on each side of the bed. The controlled traffic approach may allow more timely access to the fields for time-critical farming operations such as planting, spraying or harvesting when in conventionally designed fields conditions are unfavourable.

From the limited modelling HDP appears to offer an alternative design to combat waterlogging. These limited findings suggest that changing fields to a HDP design may allow more flexible management of the sugarcane crop as well as increasing the range of rotational crops within the sugarcane farming system.

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APPENNDIX

APPENNDIX 1A

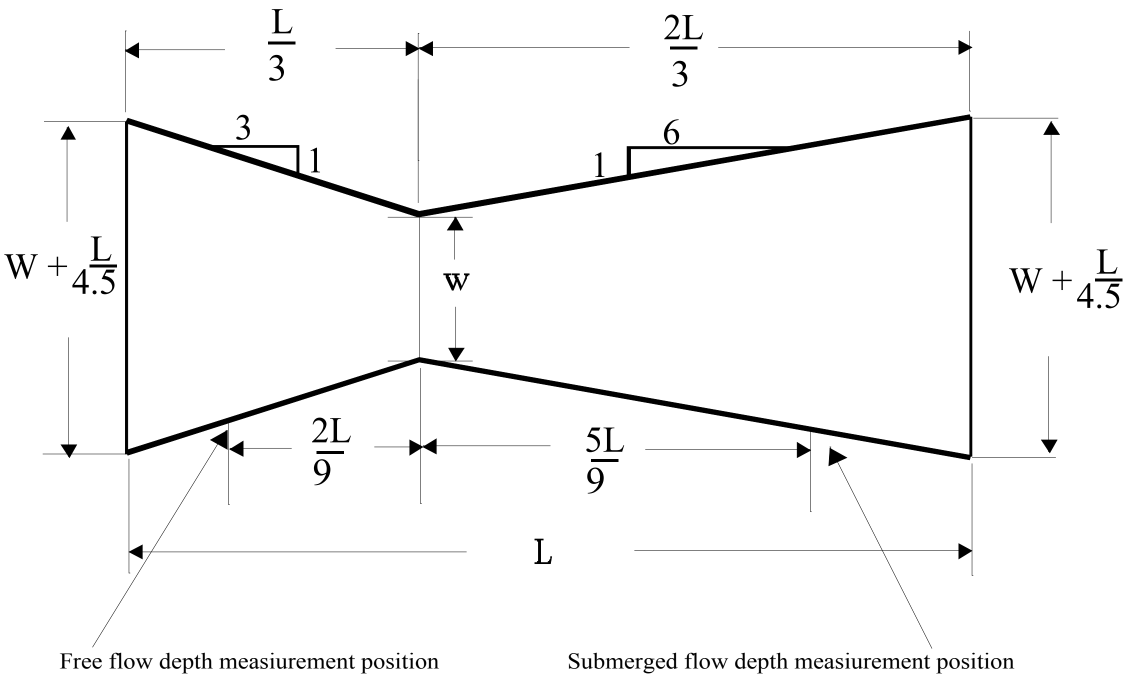

Figure 1A.1 Definition sketch of cutthroat flume (Skoerboe *et al.* 1972)

Table A1.1 Elevation measurements of field for run on experiments

Distance from end of row (m)	Height Row 1 (m)	Height Row 2 (m)	Height Row 3 (m)
0	0.24	0.19	0.19
5	0.15	0.10	0.14
10	0.11	0.08	0.10
15	0.07	0.07	0.07
20	0.05	0.06	0.05
25	0.04	0.04	0.05
30	0.03	0.02	0.03
35	0.05	0.04	0.04
40	0.05	0.02	0.03
45	0.02	0.00	0.03
50	0.02	0.00	0.01
55	0.01	0.00	0.00
60	0.00	0.00	0.00

Table A1.2 Slope, nominal flow rate, surface condition, cross sectional area and depth of flow for run on experiment

Run name	Slope	Nominal flow rate (l/s)	Trash present	Distance m	Height mm	Width of flow (mm)	Area m^2
Flat 1	Low	Low	Yes	7.5	20	400	0.008
Flat 1	Low	Low	Yes	12.5	34	450	0.015
Flat 1	Low	Low	Yes	17.5	75	550	0.041
Flat 1	Low	Low	Yes	25	20	400	0.008
Flat 2	Low	Low	Yes	7.5	60	450	0.027
Flat 2	Low	Low	Yes	12.5	47	450	0.021
Flat 2	Low	Low	Yes	17.5	80	550	0.044
Flat 2	Low	Low	Yes	25	30	425	0.013
Flat 3	Low	Low	Yes	7.5	35	450	0.016
Flat 3	Low	Low	Yes	12.5	35	450	0.016
Flat 3	Low	Low	Yes	17.5	50	450	0.023
Flat 3	Low	Low	Yes	25	22	450	0.010
Flat 4	Low	High	Yes	12.5	45	450	0.020
Flat 4	Low	High	Yes	17.5	43	450	0.019
Flat 4	Low	High	Yes	25	25	450	0.011
Flat 4	Low	High	Yes	75	14	400	0.006
Flat 5	Low	High	Yes	7.5	30	450	0.014
Flat 5	Low	High	Yes	12.5	61	525	0.032
Flat 5	Low	High	Yes	17.5	77	550	0.042
Flat 5	Low	High	Yes	25	30	425	0.013

1H	High	High	Yes	0	34	550	0.019
1H	High	High	Yes	7.5	46	700	0.032
1H	High	High	Yes	12.5	75	950	0.071
1H	High	High	Yes	17.5	66	700	0.046
1H	High	High	Yes	25	54	600	0.032
2H	High	High	Yes	0	35	550	0.019
2H	High	High	Yes	7.5	45	700	0.032
2H	High	High	Yes	12.5	77	950	0.073
2H	High	High	Yes	17.5	71	700	0.050
2H	High	High	Yes	25	55	600	0.033
3H	High	High	Yes	0	36	550	0.020
3H	High	High	Yes	7.5	45	700	0.032
3H	High	High	Yes	12.5	75	950	0.071
3H	High	High	Yes	17.5	74	700	0.052
3H	High	High	Yes	25	60	600	0.036
1LNT	High	Low	No	0	17	500	0.009
1LNT	High	Low	No	7.5	16	600	0.010
1LNT	High	Low	No	12.5	20	400	0.008
1LNT	High	Low	No	17.5	12	650	0.008
1LNT	High	Low	No	25	23	450	0.010
2LNT	High	Low	No	7.5	24.7	700	0.017
2LNT	High	Low	No	12.5	26	400	0.010
2LNT	High	Low	No	17.5	19	650	0.012
2LNT	High	Low	No	25	21	400	0.008

3LNT	High	Low	No	0	19	500	0.010
3LNT	High	Low	No	7.5	21	650	0.014
3LNT	High	Low	No	12.5	27	400	0.011
3LNT	High	Low	No	17.5	22	650	0.014
3LNT	High	Low	No	25	24	400	0.010
1HNT	High	High	No	0	40	550	0.022
1HNT	High	High	No	7.5	28.6	800	0.023
1HNT	High	High	No	12.5	30	550	0.017
1HNT	High	High	No	17.5	23	700	0.016
1HNT	High	High	No	25	60	600	0.036
2HNT	High	High	No	0	40	550	0.022
2HNT	High	High	No	7.5	26	700	0.018
2HNT	High	High	No	12.5	26.94	600	0.016
2HNT	High	High	No	17.5	40	600	0.024
2HNT	High	High	No	25	30	600	0.018
1L	High	Low	Yes	0	50	500	0.025
1L	High	Low	Yes	7.5	49	800	0.039
1L	High	Low	Yes	12.5	35	700	0.025
1L	High	Low	Yes	17.5	25	700	0.018
1L	High	Low	Yes	25	30	450	0.014
2L	High	Low	Yes	0	55	550	0.030
2L	High	Low	Yes	7.5	43	800	0.034
2L	High	Low	Yes	12.5	46	700	0.032
2L	High	Low	Yes	17.5	35	700	0.025

2L	High	Low	Yes	25	16	500	0.008
3L	High	Low	Yes	0	50	650	0.033
3L	High	Low	Yes	7.5	43	800	0.034
3L	High	Low	Yes	12.5	48	700	0.034
3L	High	Low	Yes	17.5	36	700	0.025
3L	High	Low	Yes	25	18.5	450	0.008
4L	High	Low	Yes	0	37.9	650	0.025
4L	High	Low	Yes	7.5	49	800	0.039
4L	High	Low	Yes	12.5	48	700	0.034
4L	High	Low	Yes	17.5	40	700	0.028
4L	High	Low	Yes	25	30	450	0.014

Table A1.3 Flow velocity and slope of furrow from run on experiments

Rep	Slope m/m	Flow Direction	Nominal Flow rate*	Measured inflow rate (L/s)	Surface conditions	Flow Velocity m/s
1	0.0008	Furrow	Low	Not measured	Trash	0.022
2	0.0008	Furrow	Low	Not measured	Trash	0.030
3	0.0008	Furrow	Low	Not measured	Trash	0.028
4	0.0008	Furrow	High	Not measured	Trash	0.020
5	0.0008	Furrow	High	Not measured	Trash	0.043
1	0.006	Furrow	Low	0.40	Trash	0.020
2	0.006	Furrow	Low	0.50	Trash	0.031
3	0.006	Furrow	Low	0.35	Trash	0.022
4	0.006	Furrow	Low	0.35	Trash	0.032
1	0.006	Furrow	High	1.65	Trash	0.063
2	0.006	Furrow	High	1.50	Trash	0.060
3	0.006	Furrow	High	1.60	Trash	0.089
1	0.006	Furrow	Low	0.43	No trash	0.074
2	0.006	Furrow	Low	0.51	No trash	0.078
3	0.006	Furrow	Low	0.46	No trash	0.074
1	0.006	Furrow	High	0.97	No trash	0.156
2	0.006	Furrow	High	1.18	No trash	0.156
1	0.03	90^o	High	2.5	Trash	0.028
2	0.03	90^o	High	2.0	Trash	0.027
3	0.03	90^o	High	2.5	Trash	0.024
1	0.03	45^o	High	5.3	Trash	0.026
2	0.03	45^o	High	6.58	Trash	0.027
3	0.03	45^o	High	7.25	Trash	0.038

*Water was delivered to the furrow from a flume, raised 50 mm above the height of the inter row at two nominal flow rates, high and low. The low rate was on average 0.4 L/s while the high flow rate was 1.4 l/s.

APPENDIX 2A

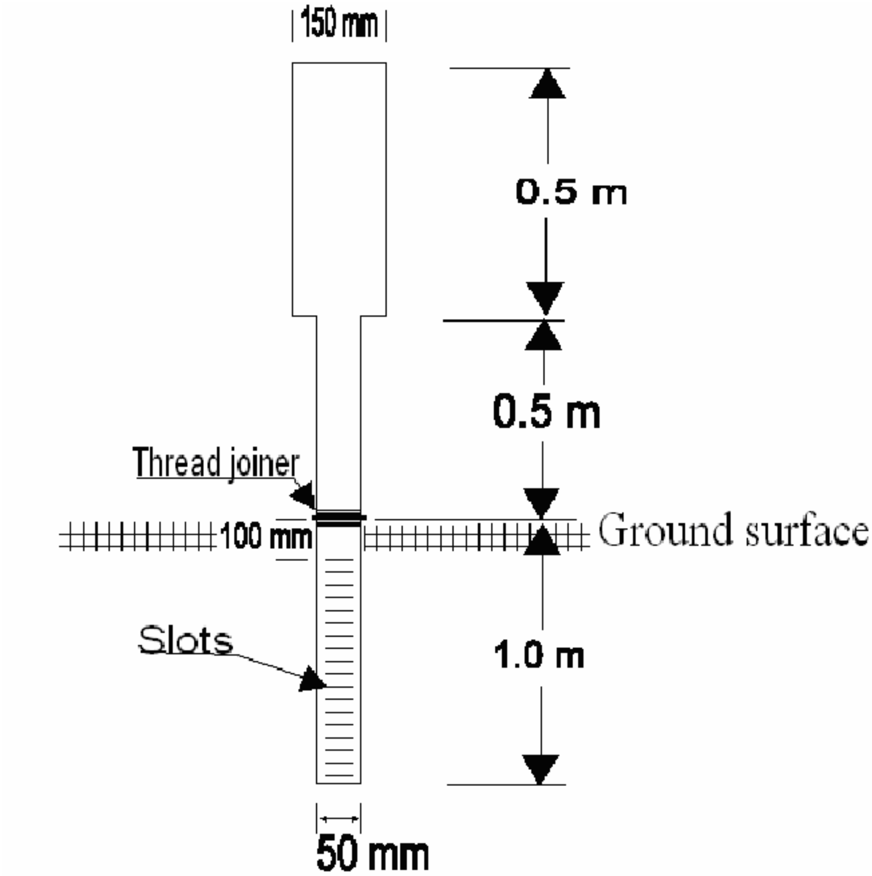

Figure A2.1 Sketch of shallow well design

$$\theta v = \frac{Core_{wet} - Core_{od}}{corevol} \qquad \text{Eqn A2.1}$$

Where

$Core_{wet}$ is the weight of wet soil in the core

$Core_{od}$ is the weight of oven dry soil in the core

Corevol is the volume of soil in the core

Output from RETC

Palmas A***

ANALYSIS OF SOIL HYDRAULIC PROPERTIES *

* Welcome to RETC *

* VARIABLE N AND M (MUALEM-THEORY FOR K) *

* ANALYSIS OF RETENTION DATA ONLY *

* MTYPE= 1 METHOD= 3 *

INITIAL VALUES OF THE COEFFICIENTS

NO	NAME	INITIAL VALUE	INDEX
1	ThetaR	.1000	1
2	ThetaS	.3950	1
3	Alpha	.4000	1
4	n	2.0000	1
5	00.5	.5000	1
6	l	.5000	0
7	Ks	1.0000	0

OBSERVED DATA

=============

OBS. NO. RESSURE HEAD WATER CONTENT WEIGHTING COEFFICIENT

1 .060 . 3940

1.0000

2 .120 . 3797

1.0000

3 .300 . 3547

1.0000

4	1.000	.	3277
1.0000			
5	3.000	.	2663
1.0000			
6	10.000		.2439
1.0000			
7	30.000		.2072
1.0000			
8	150.000		.0900
1.0000			

NIT	SSQ	ThetaR	ThetaS	Alpha	n	00.5
0	.01662	.1000	.3950	.4000	2.0000	.5000
1	.00530	.0868	.3828	.5677	1.0050	.3429
2	.00384	.0747	.3823	.6046	1.0230	.3559
3	.00366	.0682	.3831	.6088	1.0050	.3578
4	.00362	.0513	.3859	.6110	1.0050	.3553
5	.00354	.0496	.3861	.6012	1.0050	.3502
6	.00351	.0475	.3859	.5958	1.0050	.3461
7	.00348	.0454	.3857	.5922	1.0050	.3425
8	.00345	.0433	.3855	.5895	1.0050	.3391
9	.00343	.0413	.3853	.5874	1.0050	.3358
10	.00341	.0394	.3851	.5859	1.0050	.3326
11	.00339	.0375	.3850	.5849	1.0050	.3294

12	.00338	.0356	.3848	.5842	1.0050	.3264
13	.00336	.0339	.3847	.5839	1.0050	.3235
14	.00334	.0321	.3846	.5840	1.0050	.3206
15	.00333	.0305	.3844	.5844	1.0050	.3178
16	.00331	.0288	.3843	.5851	1.0050	.3151
17	.00330	.0272	.3842	.5860	1.0050	.3124
18	.00329	.0257	.3842	.5872	1.0050	.3098
19	.00327	.0242	.3841	.5886	1.0050	.3072
20	.00326	.0227	.3840	.5903	1.0050	.3047
21	.00325	.0213	.3840	.5921	1.0050	.3023
22	.00323	.0198	.3839	.5941	1.0050	.2999
23	.00322	.0185	.3839	.5963	1.0050	.2976
24	.00321	.0171	.3838	.5986	1.0050	.2953
25	.00320	.0158	.3838	.6011	1.0050	.2930
26	.00319	.0145	.3838	.6038	1.0050	.2908
27	.00318	.0132	.3838	.6065	1.0050	.2886
28	.00317	.0119	.3838	.6094	1.0050	.2865
29	.00315	.0107	.3837	.6124	1.0050	.2844
30	.00314	.0094	.3837	.6155	1.0050	.2824
31	.00313	.0082	.3837	.6187	1.0050	.2804
32	.00312	.0070	.3837	.6219	1.0050	.2784
33	.00311	.0058	.3837	.6253	1.0050	.2764
34	.00310	.0047	.3837	.6287	1.0050	.2745
35	.00309	.0035	.3837	.6322	1.0050	.2726
36	.00309	.0024	.3838	.6358	1.0050	.2708

37	.00308	.0013	.3838	.6394	1.0050	.2690
38	.00307	.0001	.3838	.6431	1.0050	.2672

NIT	SSQ	ThetaS	Alpha	n	00.5
0	.06264	.3950	.4000	2.0000	.5000
1	.02366	.3872	.6093	1.0050	.1422
2	.00317	.3818	.9999	1.0969	.1968
3	.00296	.3870	1.0298	1.0135	.2196
4	.00295	.3873	1.0339	1.0121	.2212
5	.00294	.3876	1.0350	1.0087	.2224
6	.00294	.3883	1.0242	1.0050	.2277
7	.00293	.3885	1.0186	1.0050	.2280
8	.00293	.3886	1.0145	1.0050	.2283
9	.00293	.3887	1.0111	1.0050	.2286
10	.00293	.3887	1.0102	1.0050	.2286
11	.00293	.3887	1.0093	1.0050	.2285
12	.00293	.3887	1.0086	1.0050	.2285
13	.00293	.3887	1.0079	1.0050	.2284
14	.00293	.3887	1.0072	1.0050	.2284
15	.00293	.3887	1.0067	1.0050	.2284
16	.00293	.3887	1.0061	1.0050	.2283
17	.00293	.3887	1.0056	1.0050	.2283
18	.00293	.3887	1.0051	1.0050	.2283
19	.00293	.3887	1.0047	1.0050	.2283
20	.00293	.3887	1.0043	1.0050	.2282

21	.00293	.3887	1.0042	1.0050	.2283
22	.00293	.3887	1.0038	1.0050	.2282
23	.00293	.3887	1.0038	1.0050	.2282
24	.00293	.3887	1.0038	1.0050	.2283
25	.00293	.3887	1.0038	1.0050	.2283
26	.00293	.3887	1.0034	1.0050	.2283
27	.00293	.3887	1.0034	1.0050	.2283
28	.00293	.3887	1.0034	1.0050	.2283
29	.00293	.3887	1.0030	1.0050	.2283
30	.00293	.3887	1.0030	1.0050	.2283
31	.00293	.3887	1.0030	1.0050	.2283
32	.00293	.3887	1.0026	1.0050	.2283
33	.00293	.3887	1.0026	1.0050	.2283
34	.00293	.3887	1.0026	1.0050	.2283
35	.00293	.3887	1.0022	1.0050	.2283
36	.00293	.3887	1.0022	1.0050	.2283
37	.00293	.3886	1.0021	1.0050	.2283
38	.00293	.3886	1.0021	1.0050	.2284
39	.00293	.3886	1.0017	1.0050	.2283
40	.00293	.3886	1.0017	1.0050	.2284
41	.00293	.3886	1.0017	1.0050	.2284
42	.00293	.3886	1.0013	1.0050	.2284
43	.00293	.3886	1.0013	1.0050	.2284
44	.00293	.3886	1.0013	1.0050	.2284
45	.00293	.3886	1.0009	1.0050	.2284

46	.00293	.3886	1.0009	1.0050	.2284
47	.00293	.3886	1.0009	1.0050	.2284
48	.00293	.3886	1.0005	1.0050	.2284
49	.00293	.3886	1.0005	1.0050	.2284
51	.00293	.3886	1.0005	1.0050	.2284

CORRELATION MATRIX

==================

	Theta	Alpha	n	00.5
	1	2	3	4
1	1.0000			
2	-.4807	1.0000		
3	-.8463	.8153	1.0000	
4	.7995	-.8882	-.9869	1.0000

RSQUARED FOR REGRESSION OF OBSERVED VS FITTED VALUES = .96021322

NONLINEAR LEAST-SQUARES ANALYSIS: FINAL RESULTS

==

				95% CONFIDENCE LIMITS	
VARIABLE	VALUE	S.E.COEFF.	T-VALUE	LOWER	UPPER
ThetaS	.38861	.03917	9.92	.2799	.4974
Alpha	1.00050	1.69152	.59	-3.6956	5.6966
n	1.00500	1.35855	.74	-2.7667	4.7767

00.5 .22845 .40900 .56 -.9071 1.3639

OBSERVED AND FITTED DATA

========================

NO	P	LOG-P	WC-OBS	WC-FIT	WC-DEV
1	.6000E-01	-1.2218	.3940	.3835	.0105
2	.1200E+00	-.9208	.3797	.3788	.0009
3	.3000E+00	-.5229	.3547	.3661	-.0114
4	.1000E+01	.0000	.3277	.3317	-.0040
5	.3000E+01	.4771	.2663	.2828	-.0165
6	.1000E+02	1.0000	.2439	.2241	.0198
7	.3000E+02	1.4771	.2072	.1767	.0305
8	.1500E+03	2.1761	.0900	.1228	-.0328

SUM OF SQUARES OF OBSERVED VERSUS FITTED VALUES

===

	UNWEIGHTED	WEIGHTED
RETENTION DATA	.00293	.00293
COND/DIFF DATA	.00000	.00000
ALL DATA	.00293	.00293

SOIL HYDRAULIC PROPERTIES (MTYPE = 1)

===

WC	P	LOGP	COND	LOGK	DIF	LOGD
.0010	-.1973E+12	11.295	.1399E-33	-33.854	.1213E-18	-18.916
.0020	-.9637E+10	9.984	.3317E-30	-30.479	.7023E-17	-17.153
.0040	-.4708E+09	8.673	.7865E-27	-27.104	.4067E-15	-15.391
.0079	-.2299E+08	7.362	.1865E-23	-23.729	.2355E-13	-13.628
.0119	-.3932E+07	6.595	.1757E-21	-21.755	.2530E-12	-12.597
.0159	-.1123E+07	6.050	.4421E-20	-20.354	.1364E-11	-11.865
.0198	-.4250E+06	5.628	.5395E-19	-19.268	.5037E-11	-11.298
.0238	-.1921E+06	5.283	.4166E-18	-18.380	.1465E-10	-10.834
.0278	-.9814E+05	4.992	.2346E-17	-17.630	.3613E-10	-10.442
.0317	-.5486E+05	4.739	.1048E-16	-16.980	.7896E-10	-10.103
.0357	-.3284E+05	4.516	.3926E-16	-16.406	.1574E-09	-9.803
.0397	-.2076E+05	4.317	.1279E-15	-15.893	.2917E-09	-9.535
.0436	-.1370E+05	4.137	.3724E-15	-15.429	.5097E-09	-9.293
.0476	-.9381E+04	3.972	.9879E-15	-15.005	.8483E-09	-9.071
.0516	-.6619E+04	3.821	.2423E-14	-14.616	.1356E-08	-8.868
.0555	-.4793E+04	3.681	.5563E-14	-14.255	.2092E-08	-8.679
.0595	-.3549E+04	3.550	.1206E-13	-13.919	.3134E-08	-8.504
.0634	-.2679E+04	3.428	.2486E-13	-13.604	.4574E-08	-8.340
.0674	-.2057E+04	3.313	.4906E-13	-13.309	.6524E-08	-8.185
.0714	-.1603E+04	3.205	.9314E-13	-13.031	.9119E-08	-8.040
.0753	-.1267E+04	3.103	.1708E-12	-12.768	.1252E-07	-7.902
.0793	-.1013E+04	3.006	.3036E-12	-12.518	.1691E-07	-7.772

.0833	-.8189E+03	2.913	.5248E-12	-12.280	.2250E-07	-7.648
.0872	-.6685E+03	2.825	.8843E-12	-12.053	.2956E-07	-7.529
.0912	-.5506E+03	2.741	.1456E-11	-11.837	.3836E-07	-7.416
.0952	-.4573E+03	2.660	.2347E-11	-11.629	.4923E-07	-7.308
.0991	-.3827E+03	2.583	.3711E-11	-11.430	.6255E-07	-7.204
.1031	-.3224E+03	2.508	.5764E-11	-11.239	.7875E-07	-7.104
.1071	-.2734E+03	2.437	.8805E-11	-11.055	.9828E-07	-7.008
.1110	-.2332E+03	2.368	.1325E-10	-10.878	.1217E-06	-6.915
.1150	-.2000E+03	2.301	.1965E-10	-10.707	.1496E-06	-6.825
.1190	-.1724E+03	2.237	.2876E-10	-10.541	.1826E-06	-6.739
.1229	-.1493E+03	2.174	.4157E-10	-10.381	.2214E-06	-6.655
.1269	-.1299E+03	2.114	.5941E-10	-10.226	.2669E-06	-6.574
.1309	-.1135E+03	2.055	.8398E-10	-10.076	.3200E-06	-6.495
.1348	-.9955E+02	1.998	.1175E-09	-9.930	.3816E-06	-6.418
.1388	-.8763E+02	1.943	.1629E-09	-9.788	.4529E-06	-6.344
.1428	-.7740E+02	1.889	.2237E-09	-9.650	.5350E-06	-6.272
.1467	-.6858E+02	1.836	.3047E-09	-9.516	.6292E-06	-6.201
.1507	-.6095E+02	1.785	.4117E-09	-9.385	.7370E-06	-6.133
.1547	-.5433E+02	1.735	.5520E-09	-9.258	.8599E-06	-6.066
.1586	-.4855E+02	1.686	.7349E-09	-9.134	.9996E-06	-6.000
.1626	-.4350E+02	1.638	.9718E-09	-9.012	.1158E-05	-5.936
.1665	-.3907E+02	1.592	.1277E-08	-8.894	.1337E-05	-5.874
.1705	-.3517E+02	1.546	.1667E-08	-8.778	.1539E-05	-5.813
.1745	-.3172E+02	1.501	.2164E-08	-8.665	.1767E-05	-5.753
.1784	-.2867E+02	1.457	.2794E-08	-8.554	.2022E-05	-5.694

.1824	-.2597E+02	1.414	.3588E-08	-8.445	.2309E-05	-5.637
.1864	-.2356E+02	1.372	.4585E-08	-8.339	.2630E-05	-5.580
.1903	-.2141E+02	1.331	.5831E-08	-8.234	.2988E-05	-5.525
.1943	-.1948E+02	1.290	.7383E-08	-8.132	.3387E-05	-5.470
.1983	-.1776E+02	1.249	.9307E-08	-8.031	.3832E-05	-5.417
.2022	-.1621E+02	1.210	.1168E-07	-7.932	.4327E-05	-5.364
.2062	-.1481E+02	1.171	.1461E-07	-7.835	.4877E-05	-5.312
.2102	-.1356E+02	1.132	.1820E-07	-7.740	.5487E-05	-5.261
.2141	-.1242E+02	1.094	.2260E-07	-7.646	.6163E-05	-5.210
.2181	-.1139E+02	1.057	.2796E-07	-7.553	.6912E-05	-5.160
.2221	-.1046E+02	1.019	.3449E-07	-7.462	.7740E-05	-5.111
.2260	-.9607E+01	.983	.4240E-07	-7.373	.8657E-05	-5.063
.2300	-.8834E+01	.946	.5199E-07	-7.284	.9670E-05	-5.015
.2340	-.8129E+01	.910	.6356E-07	-7.197	.1079E-04	-4.967
.2379	-.7485E+01	.874	.7751E-07	-7.111	.1203E-04	-4.920
.2419	-.6896E+01	.839	.9430E-07	-7.026	.1339E-04	-4.873
.2459	-.6357E+01	.803	.1144E-06	-6.941	.1490E-04	-4.827
.2498	-.5863E+01	.768	.1386E-06	-6.858	.1656E-04	-4.781
.2538	-.5408E+01	.733	.1675E-06	-6.776	.1840E-04	-4.735
.2578	-.4990E+01	.698	.2021E-06	-6.694	.2043E-04	-4.690
.2617	-.4605E+01	.663	.2433E-06	-6.614	.2267E-04	-4.645
.2657	-.4251E+01	.628	.2926E-06	-6.534	.2515E-04	-4.600
.2697	-.3923E+01	.594	.3512E-06	-6.454	.2789E-04	-4.555
.2736	-.3620E+01	.559	.4211E-06	-6.376	.3092E-04	-4.510
.2776	-.3340E+01	.524	.5042E-06	-6.297	.3428E-04	-4.465

.2815	-.3080E+01	.489	.6031E-06	-6.220	.3801E-04	-4.420
.2855	-.2839E+01	.453	.7208E-06	-6.142	.4215E-04	-4.375
.2895	-.2616E+01	.418	.8607E-06	-6.065	.4676E-04	-4.330
.2934	-.2408E+01	.382	.1027E-05	-5.988	.5189E-04	-4.285
.2974	-.2215E+01	.345	.1226E-05	-5.912	.5762E-04	-4.239
.3014	-.2035E+01	.309	.1462E-05	-5.835	.6404E-04	-4.194
.3053	-.1867E+01	.271	.1744E-05	-5.758	.7123E-04	-4.147
.3093	-.1711E+01	.233	.2081E-05	-5.682	.7932E-04	-4.101
.3133	-.1564E+01	.194	.2483E-05	-5.605	.8845E-04	-4.053
.3172	-.1428E+01	.155	.2967E-05	-5.528	.9879E-04	-4.005
.3212	-.1300E+01	.114	.3547E-05	-5.450	.1106E-03	-3.956
.3252	-.1180E+01	.072	.4248E-05	-5.372	.1240E-03	-3.907
.3291	-.1068E+01	.029	.5095E-05	-5.293	.1394E-03	-3.856
.3331	-.9633E+00	-.016	.6126E-05	-5.213	.1572E-03	-3.803
.3371	-.8647E+00	-.063	.7386E-05	-5.132	.1780E-03	-3.750
.3410	-.7720E+00	-.112	.8935E-05	-5.049	.2023E-03	-3.694
.3450	-.6849E+00	-.164	.1086E-04	-4.964	.2311E-03	-3.636
.3490	-.6030E+00	-.220	.1326E-04	-4.877	.2657E-03	-3.576
.3529	-.5259E+00	-.279	.1630E-04	-4.788	.3075E-03	-3.512
.3569	-.4533E+00	-.344	.2020E-04	-4.695	.3592E-03	-3.445
.3609	-.3848E+00	-.415	.2530E-04	-4.597	.4242E-03	-3.372
.3648	-.3202E+00	-.495	.3211E-04	-4.493	.5082E-03	-3.294
.3688	-.2593E+00	-.586	.4152E-04	-4.382	.6206E-03	-3.207
.3728	-.2016E+00	-.695	.5509E-04	-4.259	.7784E-03	-3.109
.3767	-.1471E+00	-.832	.7604E-04	-4.119	.1017E-02	-2.993

.3807 -.9552E-01 -1.020 .1123E-03 -3.949 .1423E-02 -2.847

.3846 -.4661E-01 -1.332 .1930E-03 -3.714 .2320E-02 -2.635

.3866 -.2306E-01 -1.637 .2970E-03 -3.527 .3485E-02 -2.458

.3876 -.1149E-01 -1.940 .4241E-03 -3.373 .4925E-02 -2.308

.3882 -.4599E-02 -2.337 .6267E-03 -3.203 .7252E-02 -2.140

.3886 -.4640E-03 -3.333 .1306E-02 -2.884 .1521E-01 -1.818

.3886 -.4693E-04 -4.329 .2220E-02 -2.654 .2614E-01 -1.583

.3886 .0000E+00 .1000E+01 .000

END OF PROBLEM ==============

Palmas B * *

ANALYSIS OF SOIL HYDRAULIC PROPERTIES *

Welcome to RETC **

* VARIABLE N AND M (MUALEM-THEORY FOR K) *

* ANALYSIS OF RETENTION DATA ONLY *

* MTYPE= 1 METHOD= 3 *

INITIAL VALUES OF THE COEFFICIENTS

===================================

NO NAME INITIAL

VALUE INDEX

1 ThetaR

0780 1

2 ThetaS

.4300 1

3 Alpha

3.600 1

4 n 1.5600

1

5 m 3590

1

6 l 5000

0

7 Ks 1.0000

0

OBSERVED DATA

=============

OBS. NO.	PRESSURE	WATER CONTENT	WEIGHTING COEFFICIENT
1	.060	.3397	1.0000
2	.120	.3433	1.0000
3	.300	.3304	1.0000
4	1.000	.3100	1.0000
5	3.000	.3020	1.0000
6	10.000	.2812	1.0000
7	30.000	.2396	1.0000
8	150.000	.1895	1.0000

NIT	SSQ	ThetaR	ThetaS	Alpha	n	m
0	.08496	.0780	.4300	3.6000	1.5600	.3590
1	.00325	.1629	.3723	4.6686	1.0050	.2410
2	.00283	.0257	.3694	5.7593	1.0050	.0772

3	.00145	.0137	.3650	6.2105	1.0298	.0799
4	.00135	.0100	.3630	5.9860	1.0264	.0803
5	.00130	.0073	.3615	5.6357	1.0201	.0804
6	.00123	.0022	.3601	5.0348	1.0111	.0806
7	.00121	.0010	.3598	4.9027	1.0091	.0807

WCR IS LESS THEN 0.001: CHANGED TO FIT WITH WCR=0.0

NIT	SSQ	ThetaS	Alpha	n	m
0	.18110	.4300	3.6000	1.5600	.3590
1	.11671	.4061	7.1592	1.0050	.0027
2	.00517	.3837	50.7180	4.9321	.0155
3	.00229	.3805	44.4314	4.3983	.0141
4	.00229	.3809	41.7257	4.4202	.0142
5	.00229	.3803	40.4459	4.4165	.0142
6	.00228	.3728	27.5340	4.3356	.0145
7	.00225	.3685	23.3012	4.3172	.0146
8	.00214	.3617	15.6805	4.2860	.0149
9	.00210	.3608	14.8381	4.3078	.0150
10	.00182	.3540	8.7271	4.3348	.0153
11	.00172	.3527	8.0201	4.3927	.0155
12	.00145	.3478	4.8380	4.4835	.0159
13	.00118	.3423	2.3917	4.6801	.0169
14	.00116	.3381	1.2805	3.9565	.0221
15	.00090	.3366	1.2609	4.0068	.0240
16	.00089	.3364	1.2318	3.8799	.0249
17	.00088	.3363	1.2011	3.7455	.0259

18	.00087	.3361	1.1681	3.6052	.0271
19	.00086	.3360	1.1326	3.4597	.0285
20	.00085	.3358	1.0945	3.3095	.0300
21	.00084	.3356	1.0542	3.1552	.0317
22	.00082	.3354	1.0124	2.9977	.0338
23	.00080	.3353	.9704	2.8379	.0360
24	.00078	.3351	.9293	2.6765	.0386
25	.00076	.3350	.8901	2.5147	.0416
26	.00073	.3350	.8535	2.3535	.0450
27	.00070	.3349	.8193	2.1943	.0488
28	.00067	.3350	.7869	2.0385	.0532
29	.00064	.3351	.7553	1.8881	.0581
30	.00061	.3353	.7235	1.7449	.0638
31	.00057	.3355	.6906	1.6109	.0701
32	.00043	.3393	.3387	1.0050	.1523
33	.00039	.3387	.3330	1.0050	.1506
34	.00038	.3383	.3298	1.0050	.1493
35	.00037	.3380	.3279	1.0050	.1484
36	.00036	.3377	.3268	1.0050	.1477
37	.00036	.3375	.3263	1.0050	.1472
38	.00036	.3374	.3261	1.0050	.1468
39	.00035	.3373	.3261	1.0050	.1464
40	.00035	.3372	.3264	1.0050	.1461
41	.00035	.3371	.3267	1.0050	.1459
42	.00035	.3371	.3272	1.0050	.1457

43	.00035	.3371	.3277	1.0050	.1455
44	.00035	.3371	.3282	1.0050	.1454
45	.00035	.3371	.3288	1.0050	.1452
46	.00035	.3371	.3294	1.0050	.1451
47	.00035	.3371	.3300	1.0050	.1450
48	.00035	.3371	.3305	1.0050	.1449
49	.00035	.3371	.3311	1.0050	.1448
51	.00035	.3371	.3323	1.0050	.1446

CORRELATION MATRIX

==================

	Theta	Alpha	n	m
	1	2	3	4
1	1.0000			
2	-.4348	1.0000		
3	-.7407	.8606	1.0000	
4	.6839	-.9316	-.9829	1.0000

RSQUARED FOR REGRESSION OF OBSERVED VS FITTED VALUES =

.98265332

==

NONLINEAR LEAST-SQUARES ANALYSIS: FINAL RESULTS

===

95% CONFIDENCE LIMITS

VARIABLE VALUE S.E.COEFF T-

VALUE LOWER UPPER

ThetaS .33707

.00845 39.91

.3136 .3605

Alpha 33227 .36949

90 -.6935 1.3581

n 1.00500 .70883

1.42 -.9629 2.9729

m .14460 .14536

.99 -.2590 .5482

OBSERVED AND FITTED DATA

========================

NO	P	LOG-P	WC-OBS	WC-FIT	WC-DEV
1	.6000E-01	-1.2218	.3397	.3361	.0036
2	.1200E+00	-.9208	.3433	.3352	.0081
3	.3000E+00	-.5229	.3304	.3325	-.0021
4	.1000E+01	.0000	.3100	.3234	-.0134
5	.3000E+01	.4771	.3020	.3050	-.0030
6	.1000E+02	1.0000	.2812	.2726	.0086
7	.3000E+02	1.4771	.2396	.2381	.0015

8	.1500E+03	2.1761	.1895	.1905	-.0010

SUM OF SQUARES OF OBSERVED VERSUS FITTED VALUES

==

	UNWEIGHTED	WEIGHTED
RETENTION DATA	.00035	.00035
COND/DIFF DATA	.00000	.00000
ALL DATA	.00035	.00035

SOIL HYDRAULIC PROPERTIES (MTYPE = 1)

====================================

Theta	Pressure (p)	LOGP	COND	LOGK	DIF	LOGD
.0069	-.1286E+13	12.109	.6221E-32	-32.206	.8005E-17	-17.097
.0103	-.7899E+11	10.898	.4546E-29	-29.342	.2395E-15	-15.621
.0138	-.1091E+11	10.038	.4891E-27	-27.311	.2669E-14	-14.574
.0172	-.2349E+10	9.371	.1843E-25	-25.735	.1732E-13	-13.761
.0206	-.6700E+09	8.826	.3574E-24	-24.447	.7985E-13	-13.098
.0241	-.2320E+09	8.365	.4384E-23	-23.358	.2906E-12	-12.537
.0275	-.9254E+08	7.966	.3846E-22	-22.415	.8900E-12	-12.051
.0310	-.4115E+08	7.614	.2611E-21	-21.583	.2389E-11	-11.622
.0344	-.1993E+08	7.299	.1449E-20	-20.839	.5776E-11	-11.238
.0378	-.1034E+08	7.015	.6826E-20	-20.166	.1284E-10	-10.891
.0413	-.5683E+07	6.755	.2810E-19	-19.551	.2663E-10	-10.575
.0447	-.3276E+07	6.515	.1033E-18	-18.986	.5208E-10	-10.283

.0482	-.1968E+07	6.294	.3447E-18	-18.463	.9692E-10	-10.014
.0516	-.1224E+07	6.088	.1059E-17	-17.975	.1728E-09	-9.762
.0550	-.7850E+06	5.895	.3024E-17	-17.519	.2968E-09	-9.528
.0585	-.5172E+06	5.714	.8104E-17	-17.091	.4933E-09	-9.307
.0619	-.3490E+06	5.543	.2053E-16	-16.688	.7965E-09	-9.099
.0654	-.2406E+06	5.381	.4946E-16	-16.306	.1253E-08	-8.902
.0688	-.1690E+06	5.228	.1139E-15	-15.943	.1926E-08	-8.715
.0722	-.1208E+06	5.082	.2519E-15	-15.599	.2899E-08	-8.538
.0757	-.8773E+05	4.943	.5367E-15	-15.270	.4282E-08	-8.368
.0791	-.6461E+05	4.810	.1106E-14	-14.956	.6215E-08	-8.207
.0825	-.4820E+05	4.683	.2209E-14	-14.656	.8879E-08	-8.052
.0860	-.3640E+05	4.561	.4291E-14	-14.367	.1250E-07	-7.903
.0894	-.2779E+05	4.444	.8121E-14	-14.090	.1737E-07	-7.760
.0929	-.2143E+05	4.331	.1500E-13	-13.824	.2383E-07	-7.623
.0963	-.1669E+05	4.222	.2711E-13	-13.567	.3232E-07	-7.490
.0997	-.1311E+05	4.117	.4797E-13	-13.319	.4338E-07	-7.363
.1032	-.1038E+05	4.016	.8325E-13	-13.080	.5764E-07	-7.239
.1066	-.8281E+04	3.918	.1419E-12	-12.848	.7587E-07	-7.120
.1101	-.6655E+04	3.823	.2378E-12	-12.624	.9901E-07	-7.004
.1135	-.5385E+04	3.731	.3923E-12	-12.406	.1282E-06	-6.892
.1169	-.4384E+04	3.642	.6376E-12	-12.195	.1646E-06	-6.784
.1204	-.3591E+04	3.555	.1022E-11	-11.991	.2099E-06	-6.678
.1238	-.2958E+04	3.471	.1616E-11	-11.792	.2659E-06	-6.575
.1273	-.2449E+04	3.389	.2524E-11	-11.598	.3346E-06	-6.476
.1307	-.2038E+04	3.309	.3895E-11	-11.410	.4185E-06	-6.378

.1341	-.1704E+04	3.231	.5944E-11	-11.226	.5204E-06	-6.284
.1376	-.1431E+04	3.156	.8975E-11	-11.047	.6437E-06	-6.191
.1410	-.1207E+04	3.082	.1342E-10	-10.872	.7920E-06	-6.101
.1445	-.1022E+04	3.009	.1986E-10	-10.702	.9697E-06	-6.013
.1479	-.8688E+03	2.939	.2914E-10	-10.536	.1182E-05	-5.927
.1513	-.7412E+03	2.870	.4237E-10	-10.373	.1434E-05	-5.844
.1548	-.6346E+03	2.803	.6111E-10	-10.214	.1732E-05	-5.761
.1582	-.5451E+03	2.736	.8743E-10	-10.058	.2084E-05	-5.681
.1617	-.4697E+03	2.672	.1242E-09	-9.906	.2498E-05	-5.602
.1651	-.4060E+03	2.609	.1750E-09	-9.757	.2983E-05	-5.525
.1685	-.3519E+03	2.546	.2451E-09	-9.611	.3550E-05	-5.450
.1720	-.3058E+03	2.485	.3408E-09	-9.467	.4211E-05	-5.376
.1754	-.2665E+03	2.426	.4710E-09	-9.327	.4979E-05	-5.303
.1789	-.2328E+03	2.367	.6470E-09	-9.189	.5868E-05	-5.231
.1823	-.2038E+03	2.309	.8836E-09	-9.054	.6897E-05	-5.161
.1857	-.1789E+03	2.253	.1200E-08	-8.921	.8084E-05	-5.092
.1892	-.1573E+03	2.197	.1621E-08	-8.790	.9451E-05	-5.025
.1926	-.1386E+03	2.142	.2179E-08	-8.662	.1102E-04	-4.958
.1961	-.1224E+03	2.088	.2914E-08	-8.535	.1282E-04	-4.892
.1995	-.1082E+03	2.034	.3879E-08	-8.411	.1488E-04	-4.827
.2029	-.9591E+02	1.982	.5141E-08	-8.289	.1724E-04	-4.764
.2064	-.8511E+02	1.930	.6784E-08	-8.168	.1992E-04	-4.701
.2098	-.7564E+02	1.879	.8916E-08	-8.050	.2299E-04	-4.639
.2133	-.6732E+02	1.828	.1167E-07	-7.933	.2647E-04	-4.577
.2167	-.5999E+02	1.778	.1522E-07	-7.817	.3044E-04	-4.517

.2201	-.5353E+02	1.729	.1979E-07	-7.704	.3494E-04	-4.457
.2236	-.4781E+02	1.680	.2563E-07	-7.591	.4006E-04	-4.397
.2270	-.4275E+02	1.631	.3309E-07	-7.480	.4586E-04	-4.339
.2304	-.3825E+02	1.583	.4260E-07	-7.371	.5244E-04	-4.280
.2339	-.3426E+02	1.535	.5468E-07	-7.262	.5990E-04	-4.223
.2373	-.3070E+02	1.487	.7001E-07	-7.155	.6835E-04	-4.165
.2408	-.2752E+02	1.440	.8941E-07	-7.049	.7794E-04	-4.108
.2442	-.2469E+02	1.392	.1139E-06	-6.943	.8882E-04	-4.052
.2476	-.2215E+02	1.345	.1449E-06	-6.839	.1012E-03	-3.995
.2511	-.1987E+02	1.298	.1839E-06	-6.735	.1152E-03	-3.939
.2545	-.1783E+02	1.251	.2330E-06	-6.633	.1311E-03	-3.882
.2580	-.1599E+02	1.204	.2947E-06	-6.531	.1492E-03	-3.826
.2614	-.1434E+02	1.157	.3724E-06	-6.429	.1699E-03	-3.770
.2648	-.1285E+02	1.109	.4701E-06	-6.328	.1935E-03	-3.713
.2683	-.1150E+02	1.061	.5930E-06	-6.227	.2205E-03	-3.657
.2717	-.1029E+02	1.012	.7477E-06	-6.126	.2515E-03	-3.600
.2752	-.9186E+01	.963	.9427E-06	-6.026	.2871E-03	-3.542
.2786	-.8188E+01	.913	.1189E-05	-5.925	.3283E-03	-3.484
.2820	-.7283E+01	.862	.1500E-05	-5.824	.3761E-03	-3.425
.2855	-.6460E+01	.810	.1894E-05	-5.723	.4319E-03	-3.365
.2889	-.5712E+01	.757	.2397E-05	-5.620	.4973E-03	-3.303
.2924	-.5030E+01	.702	.3039E-05	-5.517	.5745E-03	-3.241
.2958	-.4409E+01	.644	.3864E-05	-5.413	.6664E-03	-3.176
.2992	-.3842E+01	.585	.4933E-05	-5.307	.7768E-03	-3.110
.3027	-.3324E+01	.522	.6328E-05	-5.199	.9109E-03	-3.041

.3061	-.2850E+01	.455	.8169E-05	-5.088	.1076E-02	-2.968
.3096	-.2417E+01	.383	.1063E-04	-4.973	.1283E-02	-2.892
.3130	-.2019E+01	.305	.1399E-04	-4.854	.1548E-02	-2.810
.3164	-.1654E+01	.219	.1866E-04	-4.729	.1896E-02	-2.722
.3199	-.1319E+01	.120	.2538E-04	-4.595	.2370E-02	-2.625
.3233	-.1011E+01	.005	.3549E-04	-4.450	.3049E-02	-2.516
.3268	-.7271E+00	-.138	.5176E-04	-4.286	.4097E-02	-2.388
.3302	-.4656E+00	-.332	.8122E-04	-4.090	.5930E-02	-2.227
.3336	-.2241E+00	-.650	.1499E-03	-3.824	.1012E-01	-1.995
.3354	-.1102E+00	-.958	.2421E-03	-3.616	.1575E-01	-1.803
.3362	-.5472E-01	-1.262	.3575E-03	-3.447	.2287E-01	-1.641
.3367	-.2186E-01	-1.660	.5451E-03	-3.264	.3461E-01	-1.461
.3370	-.2203E-02	-2.657	.1187E-02	-2.925	.7570E-01	-1.121
.3371	-.2227E-03	-3.652	.2066E-02	-2.685	.1331E+00	-.876

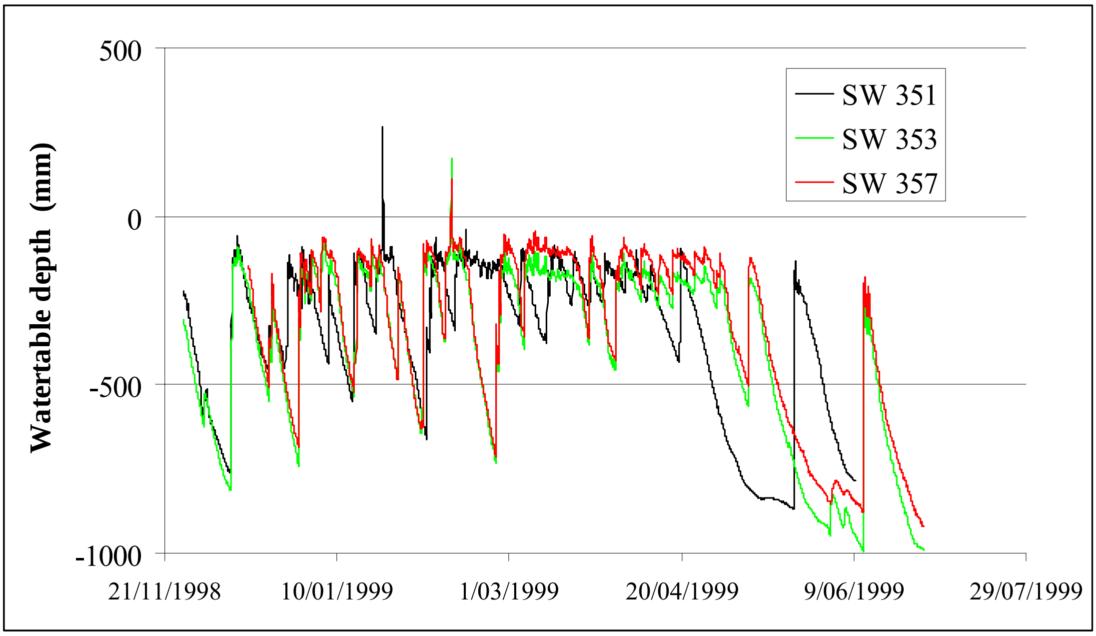

Figure A2.1 Watertable response at the Palmas Site 1998-99 for shallow wells located 350 m upslope from the main field flume

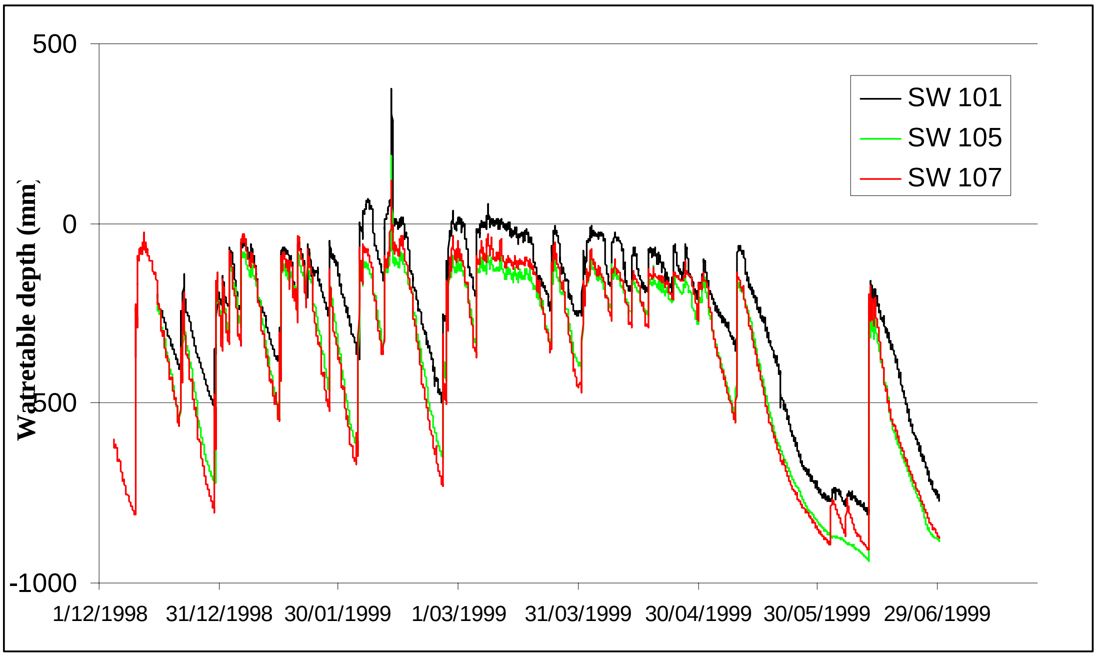

Figure A2.2 Watertable response at the Palmas Site 1998-99 for shallow wells located 100 m upslope from the main field flume

APPENDIX A3.1

Peak flow rates

Trash Blanket present

Slope 0.5%

f=y0+(a/x)

R = 0.99263849 Rsqr = 0.98533118

Adj Rsqr = 0.97799676

Standard Error of Estimate = 0.9793

	Coefficient	Std. Error	t
	P		
y0	12.5897	1.0041	
	12.5387	0.0063	
a	2926.1538	252.4577	11.5907
	0.0074		

Analysis of Variance:

		DF	SS	
	MS		F	P

Regression 1 128.8321

128.8321 134.3436 0.0074

Residual 2 1.9179

0.9590

Total 3 130.7500

43.5833

Peak flow rates

Trash Blanket present

Slope 0.125%

f=y0+(a/x)

R = 0.99141615 Rsqr = 0.98290598

Adj Rsqr = 0.97435897

Standard Error of Estimate = 0.7679

Coefficient Std. Error t

P

y0 8.1282 0.7874

10.3229 0.0093

a 2123.0769 197.9779 10.7238

0.0086

Analysis of Variance:

DF SS

MS F P

Regression 1 67.8205

67.8205 115.0000 0.0086

Residual 2 1.1795

0.5897

Total 3 69.0000

23.0000

Peak flow rates

Trash Blanket present

Slope 0.01%

f=y0+(a/x)

R = 0.99499304 Rsqr = 0.99001115

Adj Rsqr = 0.98501672

Standard Error of Estimate = 0.3789

Coefficient Std. Error t

P

y0 2.9744

0.3885 7.6555

0.0166

a 1375.38 97.6893

14.0792 0.0050

Analysis of Variance:

DF SS

MS F P

Regression 1 28.4628

28.4628 198.2232 0.0050

Residual 2 0.2872

0.1436

Total 3 28.7500

9.5833

Peak flow rates

Trash Blanket not present

Slope 0.5%

f=y0+(a/x)

R = 0.99984573 Rsqr = 0.99969148

Adj Rsqr = 0.99953723

Standard Error of Estimate = 0.1784

	Coefficient	Std. Error	t	P
y0	20.5224	0.1829	112.2229	<0.0001
a	3701.5385	45.9804	80.5025	0.0002

Analysis of Variance:

	DF	SS	MS	F	P
Regression	1	206.1551	206.1551	6480.6448	0.0002
Residual	2	0.0636	0.0318		
Total	3	206.2188	68.7396		

Peak flow rates

Trash Blanket not present

Slope 0.125

f=y0+(a/x)

R = 0.99352167 Rsqr = 0.98708531

Adj Rsqr = 0.98062797

Standard Error of Estimate = 0.9593

	Coefficient	Std. Error	t	P
y0	12.1955	0.9836	12.3989	0.0064
a	3057.6923	247.3110	12.3638	0.0065

Analysis of Variance:

	DF	SS	MS	F	P
Regression	1	140.6751	140.6751	152.8624	0.0065
Residual	2	1.8405	0.9203		
Total	3	142.5156	47.5052		

Peak flow rates

Trash Blanket not present

Slope 0.01%

f=y0+(a/x)

R = 0.99082155 Rsqr = 0.98172734

Adj Rsqr = 0.97259101

Standard Error of Estimate = 0.6455

	Coefficient	Std. Error	t	P
y0	6.0417	0.6618	9.1286	0.0118
a	1725.0000	166.4101	10.3660	0.0092

Analysis of Variance:

	DF	SS	MS	F	P
Regression	1	44.7721	44.7721	107.4531	0.0092
Residual	2	0.8333	0.4167		
Total	3	45.6055	15.2018		

APPENDIX A3.2

Recession

Trash Blanket present

Slope 0.5%

f= y0+a*x

R = 0.94796810 Rsqr = 0.89864352

Adj Rsqr = 0.84796527

Standard Error of Estimate = 0.4832

	Coefficient	Std. Error	t	P
y0	2.3000	0.5918	3.8863	0.0603
a	0.0061	0.0014	4.2110	0.0520

Analysis of Variance:

	DF	SS	MS	F	P
Regression	1	4.1405	4.1405	17.7323	0.0520

Residual 2 0.4670

0.2335

Total 3 4.6075

1.5358

Recession

Trash Blanket present

Slope 0.125%

f= y0+a*x

R = 0.94774762 Rsqr = 0.89822555

Adj Rsqr = 0.84733832

Standard Error of Estimate = 0.9314

	Coefficient	Std. Error	t	P
y0	2.8500	1.1407	2.4984	0.1297
a	0.0117	0.0028	4.2013	0.0523

Analysis of Variance:

	DF	SS	MS	F	P
Regression	1	15.3125	15.3125	17.6513	0.0523
Residual	2	1.7350	0.8675		
Total	3	17.0475	5.6825		

Recession

Trash Blanket present

Slope 0.01%

f= y0+a*x

R = 0.90868535 Rsqr = 0.82570906 Adj Rsqr = 0.73856359

Standard Error of Estimate = 1.3802

	Coefficient	Std. Error	t	P
y0	8.4500	1.6904	4.9988	0.0378
a	0.0127	0.0041	3.0782	0.0913

Analysis of Variance:

DF SS

MS

F P

Regression 1 18.0500

18.0500 9.4751 0.0913

Residual 2 3.8100

1.9050

Total 3 21.8600

7.2867

Recession

Trash Blanket not present

Slope 0.5%

f= y0+a*x

R = 0.96367132 Rsqr = 0.92866242

Adj Rsqr = 0.89299363

Standard Error of Estimate = 0.2366

Coefficient Std. Error t P

y0 2.0000 0.2898 6.9007

0.0204

a 0.0036 0.0007 5.1025

0.0363

Analysis of Variance:

DF SS

MS F P

Regression 1 1.4580

1.4580 2 6.0357

0.0363

Residual 2 0.1120

0.0560

Total 3 1.5700

0.5233

Recession

Trash Blanket not present

Slope 0.125

f= y0+a*x

R = 0.96665913 Rsqr = 0.93442987

Adj Rsqr = 0.90164480

Standard Error of Estimate = 0.6660

Coefficient Std. Error t P

y0 1.1500 0.8156 1.4100

0.2940

a 0.0106 0.0020 5.3387

0.0333

Analysis of Variance:

DF SS MS F P

Regression 1 12.6405

12.6405 28.5017 0.0333

Residual 2 0.8870

0.4435

Total 3 13.5275

4.5092

Recession

Trash Blanket not present

Slope 0.01%

f= y0+a*x

R = 0.96541746 Rsqr = 0.93203087

Adj Rsqr = 0.89804631

Standard Error of Estimate = 1.1870

Coefficient Std. Error t P

y0 2.4500 1.4538

1.6853 0.2340

a 0.0185 0.0035

5.2369 0.0346

Analysis of Variance:

DF SS

MS F P

Regression 1 38.6420

38.6420 27.4251 0.0346

Residual 2 2.8180

1.4090

Total 3 41.4600

13.8200

APPENDIX A3.3

Watertable response to wet season rainfall

Water furrow present

f= y0+a*x

R = 0.76842940 Rsqr = 0.59048375

Adj Rsqr = 0.53198142

Standard Error of Estimate = 16.3036

Coefficient Std. Error t P

y0 66.7330 16.2013 4.1190

0.0045

a 0.0331 0.0104 3.1770

0.0156

Analysis of Variance:

DF SS MS F P

Regression 1 2682.8957

2682.8957 10.0933 0.0156

Residual 7 1860.6598

265.8085

Total 8 4543.5556

567.9444

No water furrow

f=y0+a*x

R = 0.72504279 Rsqr = 0.52568705

Adj Rsqr = 0.45792806

Standard Error of Estimate = 13.4505

	Coefficient	Std. Error	t	P
y0	88.9278	13.3661	6.6533	
	0.0003			
a	0.0240	0.0086		
	2.7854	0.0271		

Analysis of Variance:

		DF	SS	
	MS		F	P
Regression		1	1403.5844	
	1403.5844	7.7582		0.0271
Residual		7	1266.4156	
	180.9165			
Total		8	2670.0000	
	333.7500			

APPENDIX A3.4

Watertable above 0.5 m v rainfall 130 after plant/harvest

Water furrow present

f= y0+a*x

R = 0.98174241 Rsqr = 0.96381816

Adj Rsqr = 0.95175754

Standard Error of Estimate = 4.5772

Coefficient Std. Error t P

y0 23.9638 5.6124

4.2698 0.0236

a 0.0567 0.0063 8.9395

0.0030

Analysis of Variance:

DF SS MS

F P

Regression 1 1674.2948

1674.2948 79.9145 0.0030

Residual 3 62.8532 20.9511

Total 4 1737.1480

434.2870

No water furrow

f= y0+a*x

R = 0.97611316 Rsqr = 0.95279690

Adj Rsqr = 0.93706254

Standard Error of Estimate = 4.0282

	Coefficient	Std. Error	t	P
y0	48.6118	4.9393	9.8419	0.0022
a	0.0435	0.0056	7.7817	0.0044

Analysis of Variance:

	DF	SS	MS	F	P
Regression	1	982.6004	982.6004	60.5552	0.0044
Residual	3	48.6796	16.2265		
Total	4	1031.2800	257.8200		

APPENDIX A3.5

Cane Yield v Plant/harvest date

Field Water furrows

Rudd and Chardon

f= y0+a*x

R = 0.95156176 Rsqr = 0.90546978

Adj Rsqr = 0.87395970

Standard Error of Estimate = 0.8424

	Coefficient	Std. Error	t	P
y0	39.6533	2.5586	15.4980	0.0006
a	1.4280	0.2664	5.3606	0.0127

Analysis of Variance:

DF SS MS F P

Regression 1 20.3922

20.3922 28.7359 0.0127

Residual 3 2.1289

0.7096

Total 4 22.5212

5.6303

Cane Yield v Plant/harvest date

Field No Water furrows

Rudd and Chardon

f= y0+a*x

R = 0.77870135 Rsqr = 0.60637579

Adj Rsqr = 0.47516772

Standard Error of Estimate = 0.6948

Coefficient Std. Error t

P

y0 50.5277 2.1104

23.9419 0.0002

a 0.4724 0.2197

2.1498 0.1207

Analysis of Variance:

DF SS MS F

P

Regression 1 2.2313 2.2313

4.6215 0.1207

Residual 3 1.4484 0.4828

Total 4 3.6797 0.9199

Cane Yield v Plant/harvest date

Field Water furrows

Gayle

f= y0+a*x

R = 0.95463499 Rsqr = 0.91132797

Adj Rsqr = 0.88177063

Standard Error of Estimate = 3.0941

Coefficient Std. Error t

P

y0 92.0849 9.3975

9.7988 0.0023

a -5.4329 0.9784 -

5.5527 0.0115

Analysis of Variance:

	DF	SS	MS	F	P
Regression	1	295.1693	295.1693	30.8325	0.0115
Residual	3	28.7199	9.5733		
Total	4	323.8892	80.9723		

Cane Yield v Plant/harvest date

Field No Water furrows

Gayle

f= y0+a*x

R = 0.99861246 Rsqr = 0.99722684 Adj Rsqr = 0.99630246

Standard Error of Estimate = 0.6459

	Coefficient	Std. Error	t	P
y0	94.6070	1.9617	48.2280	<0.0001
a	-6.7083	0.2042	-32.8451	<0.0001

Analysis of Variance:

	DF	SS	MS	F	P
Regression	1	450.0104	450.0104	1078.7997	<0.0001
Residual	3	1.2514	0.4171		
Total	4	451.2618	112.8155		