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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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)αḍ<V/K̃ı
i=1 when (Ho/D)αḍ>V/Kı

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 (^oC)
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
$t_{\frac{t_p}{e}}$ 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)