OPTIMISING RUNOFF TO BASIN RATIOS FOR MAIZE PRODUCTION WITH IN-FIELD RAINWATER HARVESTING

by

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Department of Soil, Crop and Climate Sciences

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Bloemfontein

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DECLARATION

I declare that the dissertation hereby submitted by me for the degree of Doctor of Philosophy at the University of the Free State in my own independent work and has not previously been submitted by me at another university or faculty. I furthermore cede copyright of the dissertation in favour of the University of the Free State.

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Date: January 2012

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LIST OF SYMBOLS AND ABBREVIATIONS

a	coefficient of slope of linear equation
AI	aridity index (unit less)
Alt	Altitude (m)
ARC-ISCW	Agricultural Research Council - Institute for Soil, Climate and Water
b	coefficient of intercept of linear equation
BD	bulk density (Mg m^3)
BLAR	basin leaf area ratio
$\mathbf{C_d}$	specific heat dry mineral soils (840 J kg^{-1} $^oC^{-1}$)
CER	cumulative evaporation reduction
C_p	specific heat of air at a specific atmospheric pressure (J kg^{-1} K^{-1})
CPF	cumulative probability function
$\mathbf{C_s}$	specific heat of the soil (J kg^{-1} $^oC^{-1}$)
CS%	canopy shade percentage
CV	coefficient of variance
$\mathbf{C_w}$	specific heat soil water (4180 J kg^{-1} $^oC^{-1}$)
d	zero plane displacement (m)
D	deep drainage (mm)
DAP	days after planting
DC	drying cycle
D-index	index of agreement
DM	dry matter production (kg ha^{-1})
DOY	day of the year
dT_s	change in the soil temperature (^oC)
DUL	drained upper limit of plant available water (mm)
ea	vapor pressure of the air (KPa)
EF	fraction on available energy
$\mathbf{E_{pot}}$	potential evapotranspiration (mm d^{-1})
Es	soil water evaporation (mm)
es	saturated vapour pressure (KPa)
Es-2	second phase soil evaporation
Es-l	first phase soil evaporation
ET	evapotranspiration (mm)
ETo	reference crop evaporation (mm)
Ev	transpiration (mm)
F	generalized stability factor
FAO	Food and Agricultural Organization of the United Nations
FC-BA	full shade basin area
FC_{eff}	canopy fraction effectivity
FC-RA	full shade runoff area
FI	fraction of precipitation for a growing season
g	gravitational acceleration (9.8 m s^{-2})
G	soil heat flux (W m^{-2})
$\mathbf{G_{sf}}$	soil heat flux at the surface (W m^{-2})
h_c	canopy height (m)
HI	harvest index
Hs	sensible heat flux (W m^{-2})
$\mathbf{Hs_c}$	sensible heat flux from canopy (W m^{-2})

$\mathbf{Hs_s}$	sensible heat flux from soil surface (W m^{-2})
i	number of time increments
$\mathbf{I_{BA}}$	infiltration in the basin area
$\mathbf{I_{BA}:I_{RA}}$	infiltration ratio of basin area to runoff
I_f	infiltration rate (mm h^{-1})
IFPRI	International Food Policy Research Institute
$\mathbf{I_{RA}}$	infiltration in the runoff area
IRWH	in-field rainwater harvesting
k	von Karman constant0.41
K	transpiration efficiency coefficient (g m^{-2} mm^{-1})
$\mathbf{K_{cover}}$	coefficients factor
Kh	coefficient of heat
Kw	coefficient water vapour
L	Obukhov buoyancy length.
LAI	leaf area index
L_c	inter-row/canopy width (m)
LE	latent heat flux (W m^{-2})
$\mathbf{LE_c}$	latent heat flux from canopy (W m^{-2})
$\mathbf{LE_s}$	latent heat flux from soil surface (W m^{-2})
LL	lower limit of plant available water (mm)
LP	"*lower portion*" of canopy
$\mathbf{M_a}$	molecular mass of air
MAE	mean absolute error
MC	mulch cover (t ha^{-1})
ML	mulch level (%)
MLy	microlysimeter
M-O	Monin-Obukhov
MU	"*mid-upper*" of canopy
$\mathbf{M_w}$	molecular mass of water
NWM	neutron water meter
P	precipitation (mm)
P'	correction factor equal to (P'= 1-0.046*LAI),
PAR	photo synthetically active radiation (MJ s^{-1} m^{-2})
PAWC	plant available water capacity (mm)
PC-RA	partial shade runoff area
$\mathbf{P_e}$	seasonal rainfall plus run-on (mm)
$\mathbf{P_f}$	rainfall during the fallow period (mm)
$\mathbf{P_g}$	rainfall during the growing period (mm)
Pi	rainfall intensity for the particular time segment
P_o	standard atmospheric pressure at sea level (101.3 KPa)
PUE	precipitation use efficiency
PUE*fg*	precipitation use efficiency for fallow and growing season (kg ha^{-1} mm^{-1})
q	specific humidity
R	Universal gas constant (8.315411 $Jmol^{-1}K^{-1}$)
$\mathbf{R^2}$	coefficient of determination
RA	runoff area for each 1m (RA1, RA2 and RA3) of runoff strip
$\mathbf{R_{above}}$	PAR measurement above mulch cover
$\mathbf{R_{beneath}}$	PAR measurement underneath mulch cover
RCI	rainfall canopy interception (mm)
RF	amount rainfall (mm)

RF_{event}	amount rainfall event (mm) represents a group of rainstorms in 24 hrs
RH	relative humidity (%)
Ri	Richardson Number (unit less)
RMLF	runoff mulch level factor
RMSEs	systematic root mean squared error
RMSEu	unsystematic root mean squared error
Rn	net radiation (W m^{-2})
Rn_c	net radiation at canopy (W m^{-2})
Rn_s	net radiation at soil surface (W m^{-2})
Ro	in-field runoff (mm)
R_{off}	runoff (mm)
R_{on}	run-on (mm)
RR ratio	runoff to rainfall ratio
Rs	solar radiation (MJ m^{-2} day^{-1})
RSE	rainfall storage efficiency (%)
RSL	runoff strip length (m)
RWP	rainwater productivity (kg ha^{-1} mm^{-1})
RWPn	rainwater productivity over a period of n consecutive years (kg $ha^{-1}mm^{-1}$)
S_{max}	maximum amount of rain that the canopy intercepts (mm)
SPAC	soil-plant-atmosphere continuum
SWC	soil water content (mm)
t	time after drainage started (h)
t	time of day (h)
TDM	total above-ground biomass (kg ha^{-1})
ti	time interval (min)
T_{max}	daily maximum temperature (ºC)
T_{mean}	mean daily temperature (ºC)
T_{min}	daily minimum temperature (ºC)
t_o	time of the solar noon
TRR	total runoff-rainfall ratio
u	wind speed (m s^{-1})
$u_2 - u_1$	difference in wind speed at two levels (m s^{-1});
UC-RA	unshaded cover runoff area
UNEP	United Nations Environmental Programme
UP	"*upper portion*" of canopy
USDA	United States Department of Agriculture
VPD	vapour pressure deficit (KPa)
WP_{Ev}	water productivity calculated with transpiration
WRC	Water Research Commission
WUE	water use efficiency (kg ha^{-1} mm^{-1})
Yg	grain yield (kg ha^{-1})
z	measurement height (m);
$z_2 - z_1$	height interval (m)
z_m	height in the surface layer (m)
z_o	roughness length parameter

$\boldsymbol{\rho_w}$	water density (Mg kg^{-3})
$\boldsymbol{\epsilon_s}$	soil emissivity
$\sum$Es	cumulative soil water evaporation
$\sum$RF	total precipitation over n consecutive years (mm)
$\sum$Ro	total runoff during the growing season (mm)
$\boldsymbol{\sum Ro_{bare}}$	total runoff from the bare (mm)
$\boldsymbol{\sum Ro_{mulched}}$	total runoff from the mulched (mm)
$\boldsymbol{1 - V_{sky}}$	view fraction factor of the canopy from the soil surface
Ø	latitude of the location,
$\boldsymbol{\alpha}$	albedo
$\boldsymbol{\alpha'}$	Ritchie model coefficient
$\boldsymbol{\alpha_c}$	canopy albedo
$\boldsymbol{\alpha_{s\theta}}$	soil surface albedo
$\boldsymbol{\beta}$	Bowen ratio
$\boldsymbol{\beta'}$	Stroosnijder model coefficient
$\boldsymbol{\gamma}$	psychrometeric constant
$\boldsymbol{\gamma_o}$	psychometric constant at sea-level pressure
$\boldsymbol{\delta}$	solar declination as a function of the day of year
$\boldsymbol{\Delta S}$	change in soil water storage (mm)
$\boldsymbol{\zeta_m}$	similarity stability parameter (z_m/L)
$\boldsymbol{\theta}$	potential temperature (K)
$\boldsymbol{\theta'}$	zenith angle of the sun (^{o})
$\boldsymbol{\theta_1 - \theta_2}$	difference in potential temperature at two levels (K)
$\boldsymbol{\theta_{h(n-1)}}$	root zone water content at planting of the current crop (mm)
$\boldsymbol{\theta_m}$	mass basis soil water content (kg of water per kg of dry soil)
$\boldsymbol{\theta_{p(n)}}$	root zone water content at planting of the current crop (mm)
θv	virtual potential temperature (K)
$\boldsymbol{\theta'_v}$	volumetric soil water content
$\boldsymbol{\rho_a}$	air density (1.4 kg m^{-3})
$\boldsymbol{\sigma}$	Stefan-Boltzmann constant (5.6697×10^{-8} W $m^{-2}K^{-4}$)
$\boldsymbol{\phi_h}$	stability function for heat
$\boldsymbol{\phi_m}$	stability function for momentum
$\boldsymbol{\phi_w}$	stability function for water vapour

ABSTRACT

OPTIMISING RUNOFF TO BASIN RATIOS FOR MAIZE PRODUCTION WITH IN-FIELD RAINWATER HARVESTING

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Food production in semi-arid areas principally depends on the availability of water. Consequently, improving rainwater productivity and modifying the available energy for unproductive water losses is an important and necessary step towards promoting rainfed agriculture in dryland farming. It has been convincingly argued that water management strategies on rainfed semi-arid areas, including in-field rainwater harvesting (IRWH) deserve considerable attention. However, integrated studies of water and energy balance on the IRWH technique in particular in optimizing runoff to basin area ratio and mulching levels (ML) was not comprehensively appraised. Therefore, in this thesis, the two main research questions concern: (i) what is the optimal runoff to basin area ratio to sustain maize crop yield? and (ii) how do the microclimatic conditions change under wide and narrow runoff strip length (RSL)?

Field experiments were conducted (2007/08 and 2008/9) on the Kenilworth Bainsvlei ecotope, associated with high evaporative demand of 2294 mm per annum and relatively low and erratic rainfall (528 $\pm$ 155.6 mm). Topographically the area had a gentle slope (< 1%) with reddish brown in colour (Amalia family) a fine sandy loam texture soil, thus was classified as a Bainsvlei form. The soil is regarded as very suitable for dryland agriculture, because it is deep (2000 mm) and drains freely in the top and the upper sub-soil. So the study was performed by quantifying and evaluating the soil-crop-atmosphere parameters. In the first part of the thesis, the soil water balance components and different efficiency parameters were assessed. In the second part of the thesis, the micrometeorological variable profiles within and above the maize canopy for the heat and water vapour exchange processes were characterized. Furthermore, comparison of available

energy for evapotranspiration (ET) was evaluated for both wide and narrow runoff strips through the quantification of energy balance components.

A multiple regression model was developed to predict in-field runoff by combining the effects of rainfall event characteristics and surface treatments. From the results of runoff-rainfall (RR) ratio a lower efficiency was observed from full mulch covered wide runoff strip length (RSL-3) i.e. only about 4% of the rainfall, while the highest mean RR was about 27% from bare, narrow RSL-1. From the estimation of rainfall canopy interception (RCI) it was revealed that the highest interception was in the range of 4.5% to 9.0% of the precipitation. The RCI capacity of a maize field under IRWH reached a plateau at about 0.5 – 0.6 mm for narrow RSL and 1.0 – 1.1 mm for wide that would be evaporated eventually from the canopy. Furthermore the cumulative Es ($\sum$Es) was evaluated as influenced by both mulch ("*dry-mulch*") and shading ("*green-mulch*") effects. Thus, the proportion of water loss by Es from seasonal rainfall is about 62%, 64% and 66% in the bare treatments and as low as 28%, 30% and 32% for full mulch cover treatments under full shade, (FC), partial canopy shaded (PC) and unshaded (UC) respectively. This implies that, reduction of runoff and evaporation losses through surface treatments can promote improved water use efficiency, of the stored available water in the root zone and thus, enhance yield. The final grain yield decreased slightly as an order of increasing the length of the runoff strip. The performance of the harvest index (HI) was slightly variable among the treatments due to more water for yield being collected from bare plots than mulch covered plots. The higher mulch conserves much water by suppressing the soil evaporation. In expressing grain yield per unit ET (WUE_{ET}) and transpiration, Ev (WP_{Ev}) the RSL-2 m and RSL-1.5 m at lower mulch cover showed significant higher values than RSL-1 and RSL-3 treatments. However, the transpiring water for yield and unproductive evaporation losses more under IRWH should be evaluated in terms of micrometeorological profile characterization and available energy.

With regard to micrometeorological variables, the growth stage had a strong effect on the vertical profiles of climatic variables. In wide runoff strips lapse conditions extended from lowest measurement level (LP) to the upper middle section (MU) of the canopy and inversion was apparent at the top layer (UP) of the canopy. The reason for the extension of temperature inversion into the upper part of the wide RSL canopy was as a result of higher air movements

compared to narrow strips. From this result it was confirmed that the effect of wind on water vapour removal decreased downward from wind flow within the canopy. This had an influence on the resistance of the boundary layer and canopy and soil surface resistance. This is a clear indication that wide strips supply more drying power to respond to evaporative demand of the atmosphere compared to narrow strips. From the measurement of profiles within and above the canopy, it was suggested that, the presence of local advection in the wide runoff strips of IRWH could be a common phenomenon causing variations in water vapour removal under the heterogeneous nature of IRWH tillage system. Thus, profile characteristics within and above a plant canopy are playing a great role in determining the vapour pressure deficit and consequently, can explain the ET rate. Therefore based on micrometeorological measurements, results indicated that the latent heat (LE) was dominant and higher in wide compared to narrow runoff strips (RSL) under both dry and wet conditions. However, sensible heat (Hs) showed lower values on wide runoff strips during wet conditions due to the advective effect of the runoff area. Thus, the wide runoff strip with a higher basin leaf area ratio (BLAR) of 2.43 had higher ET and used more energy in evaporating water than the narrow runoff with a lower BLAR of 1.42. Wide runoff strips converted the higher available energy more efficiently into a higher biomass production. During wet days, the wide RSL used more than 70% of the available energy for evapotranspiration, while the narrow RSL response to the available energy (63%) was stronger during dry compared to wet days. In general the wide and narrow RSL used the available water and energy differently during dry and wet conditions under IRWH system.

From this experiment finding, important implications were described such as better yield obtained from narrow RSL-1, however RSL-1.5 and 2 m with minimum mulch cover gave higher water productivity compared to narrow RSL-1 and wide RSL-3. On the other hand when quantifying and evaluating the cause behind the effect of available energy, the wide RSL converted available energy more efficiently into higher biomass production than the narrow RSL. Therefore, this challenge should be addressed on the basis of an integrated approach to water and energy resources in order to develop comprehensive management strategies. Furthermore, for improved rainwater use management strategies, it is recommended to link an integrated approach of water and energy resources with crop growth simulation models. The application of the crop models could be important by incorporating a range of planting dates and densities along with the selection of surface treatment management strategies.

Keywords: Semi-arid, maize, in-field rainwater harvesting, runoff strip length, mulch level, in-field runoff, evaporation losses, water balance, energy balance, micrometeorological vertical profiles, evapotranspiration, latent heat flux, sensible heat flux, rainwater productivity.

ABSTRACT

OPTIMISING RUNOFF TO BASIN RATIOS FOR MAIZE PRODUCTION WITH IN-FIELD RAINWATER HARVESTING

UITTREKSEL [Afrikaans]

OPTIMISERING VAN AFLOOP TOT BAKKIE VERHOUDING VIR DIE PRODUKSIE IN MIELIE ONDER OPLAND- REëNWATERINSAMELING PRAKTYKE

deur

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Ph.D. in Landbouweerkunde van die Universiteit van die Vrystaat

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Voedsel produksie in semi-aried gebiede is hoofsaaklik afhanklik van die beskikbaarheid van water. Gevolglik is verbetering van reënwaterproduktiwiteit en wysiging van die beskikbare energie vir onproduktiewe waterverliese ‘n belangrike en noodsaaklike stap tot bevordering van landbou by boerderye. Daar is oortuigend aangevoer dat waterbestuurstrategië op droëland semi-ariede gebiede, insluitend opland reënwaterinsameling (“IRWH”) heelwat aandag verdien. Nietemin is geintegreerde bestudering van water- en energiebalanse op die tegniek van “IRWH”; spesifiek by die optimisering van die afloop tot opgaringsarea verhoudings en deklaag vlakke. Daarom is die twee vernaamste navorsingsvrae in hierdie proefskrif as volg: (i) wat is die optimale afloop tot bakkiestrookverhouding om mieliegewasopbrengs volhoubaar te maak en (ii) hoe verander die mikro-klimaattoestande onder wye en smal afloop strooklengte (“RSL”)?

Veldproewe is op die Kenilworth Bainsvlei ekotoop uitgevoer (2007/08 en 2008/9) wat geassosieer ward met’ n hoë verdampingsaanvraag van 2294 mm jaar^{-1} en relatiewe lae en wisselvallige reënval (528 mm, std. $\pm$ 155.6 mm). Topografies het die gebied ‘n effense helling (< 1%), die grond is rooibruin van kleur (Amalia familie) met ‘n fyn sanderige leem tekstuur en geklassifiseerd as Bainsvlei vorm. Die grond word hoogs gepas geag vir droëland landbou omdat dit diep is (2000 mm) en op goeie interne dreineringsperspektief beskik. Dus is die studie uitgevoer deur kwantifisering en evaluering van die grondwater-gewas-atmosfeer parameters. In die eerste gedeelte van die proefskrif is die grondwaterbalans komponente en verskillende doeltreffendheids parameters evalueer. In die tweede gedeelte van die proefskrif is die mikrometeorologiese veranderlike profiele binne-in en bokant die milieblaardak vir hitte- en waterdamp uitruilingsprosesse gekarakteriseer. Verder is die vergelyking van beskikbare energie vir evapotranspirasie (ET) vir wye- en smal afloopstroke deur middel van kwantifikasie van energiebalans komponente ge-evalueer.

‘n Veelvoudige regressiemodel is ontwikkel om opland afloop te voorspel deur die kombinering van die uitwerking van reënval kenmerke en oppervlak behandelings. Die resultate van afloop-reënval (“RR”) verhoudings dui dat ‘n laer doeltreffendheid by volle deklaag wye afloop strook lengte (“RSL-3”) waargeneem d.w.s. slegs 4% van die reënval, terwyl die hoogste gemiddelde “RR” ongeveer 27% vanaf die kaal-noue RSL-1 behandeling is. Uit die berekening van reënvalblaardak onderskepping (“RCI”) het dit aan die lig gekom dat die hoogste onderskepping in die omgewing van 4.5% tot 9.0% van die reenval voorgekom het. Die “RCI” kapasiteit van die mielieland onder “IRWH” het ‘n plato by ongeveer 0.5 – 0.6 mm vir noue “RSL en 1.0 – 1.1 mm vir wye bereik wat uiteiendelik vanaf die blaardak sou verdamp. Verder is die kumulatiewe Es (∑Es) ge-evalueer soos beinvloed deur deklaag (“dry-mulch”) en skadu (“green-mulch”) uitwerkings. Dus is die proporsie waterverlies vanaf seisoenale reënval ongeveer 62%, 64% en 66% in die kaal behandelings en so laag as 28%, 30% and 32% vir volle deklaag behandelings onder volskadu (“FC”) en gedeeeltelike blaardak skadu (“PC”) en geen skadu (“UC”), respektiewelik. Dit impliseer dat vermindering van afloop en verdampingsverliese deur oppervlak behandelings (“RSL” en “ML”) ‘n verbeterde waterverbruiksdoeltreffendheid vanaf die gestoorde beskikbare water in die wortelsone kan bevorder en dus opbrengs verhoog.

Die finale graanopbrengs het effens verminder met toename in die grootte van die afloopstrook.
Die prestatsie van die oesindeks (“HI”) is effens veranderlik tussen behandelings as gevolg van meer water wat opgevang is in die bakkies vanaf kaal proewe as by deklaag proewe. Hoër deklaag bewaar meer water deur onderdrukking van grondverdamping. By uitdrukking van waterverbruiksdoeltreffendheid (WUE) per eenheid evapotranspirasie (ET) en Ev het die RSL-2m en RSL-1.5 m by laer deklaag betekenisvolle hoër waardes as die RSL-1 en RSL-2 behandelings gewys. Nietemin, behoort die transpirende water vir opbrengs en onproduktiewe verdampingsverliese, d.w.s. ET= Ev + Es onder “IRWH” geëvalueer te word in terme van mikrometeorologiese profiel karakterisering en beskikbare energie.

Met betrekking tot die mikro-meteorologiese veranderlikes het die groeistadium ‘n sterk uitwerking op die vertikale profiel gehad. In die wye afloop strook verval het toestande vanaf laagste lesingvlak (“LP”) to by die boonste middelste gedeelte (“MU”) gestrek en inversie het klaarblyklik in die boonste lae van die blaardak plaasgevind. Die rede vir die verlenging van temperature inversie tot in die boonste gedeelte van die wye blaardak is as gevolg van sterker lug beweging vergeleke met die smal afloopstroke. Vanuit die resultaat is die effek van die wind op waterdamp verwyding toegeskryf aan ‘n afname afwaarts deur oorgeplaaste windvloei binne die blaardak. Dit het ‘n invloed op die weerstand van die grenslaag en blaardak en grondoppervlakweerstand gehad. Dite is ook ‘n duidelike verwysing na die wye stroke wat meer verdrogingskrag t.o.v die verdampingsaanvraag van die atmosfeer vergeleke met die smal stroke openbaar. Vanuit die profiel lesings binne en aan die bokant van die blaardak is die voorstel gemaak dat die teenwoordigheid van lokale adveksie in die wye afloopstroke by “IRWH” ‘n algemene verskynsel is, en wat tot variasie in waterdamp verwydering onder die heterogene natuur van die “IRWH” grondbewerkingsisteem lei. Dus sal profiel kenmerke binne en bokant ‘n plant blaardak ‘n groot rol by bepaling van die “VPD” en gevolglik verduidelik dit ook die “ER” tempo speel.

Dus, gebasseer op die mikrometeorologies lesings het resultate aangedui dat die latent hitte (“LE”) dominant en hoër in die wye vergeleke met smal afloop stroke (“RSL”) gedurende beide droë en nat toestande was. Nietemin het waarneembare hitte (“Hs”) laer waardes by wye afloop stroke tydens nat toestande as gevolg van adveksie effek van die afloop gebied gewys. Dus het die wye afloop strook met ‘n hoër stroomgebied blaar area verhouding (“BLAR”) van 2.43 meer ET en meer energie verbruik by verdamping van water vergeleke met smal afloop met ‘n laer “BLA” verhouding van 1.42. Wye afloop stroke het die hoër beskikbare energie meer doeltreffend omgeskakel tot hoër biomassa produksie. Gedurende nat dae het die wye afloopstroke meer as 70% van die beskikbare energie gebruik, terwyl die smal afloopstroke reaksie tot die beskikbare energie (63%) sterker gedurende droë vergelek met nat dae voorgekom het. Oor die algemeen het die wye en smal afloopstroke die beskikbare water en energie verskillend gedurende droë en nat toestande onder die “IRWH” sisteem gebruik.

Uit hierdie eksperimentele bevinding is belangrike implikasies beskryf omdat beter opbrengs behaal is uit die wye afloopstroke RSL-1, alhoewel afloopstroke RSL-1.5 en 2 m met minimum deklaag hoër water produktiwitet gelewer het vergeleke met die smal afloopstroke RSL-1 en wye afloopstroke RSL-3. Aan die anderkant, by kwantifikasie en evaluasie van die oorsaak van die effek van beskikbare energie het die wye afloopstroke die beskikbare energie meer effektief na hoër biomassa produksie omgeskakel. Daarom behoort die uitdaging op die basis van ń geïntegreerde benadering tot water en energie hulpbronne aangespreek te word vir die ontwikkeling van alomvattende bestuurstrategieë. Verder, vir verbeterde reënwaterverbruiksbestuurstrategieë, is die aanbeveling om die geintegreerde benadering tot water en-energiehulpbronne te skakel met gewasgroei simulasie modelle. Die toepassing van die gewasgroeimodelle sal van groot belang wees indien die aanplantingsdatum en plant digtheid tesame met die seleksie van oppervlakbehandeling bestuurstrategieë ingelyf word.

Sleutelwoorde: Semi-aried ekotoop, mielies, opland waterinsameling, afloop strooklengte, deklaagvlak, opland-afloop, verdampingsverliese, waterbalans, energiebalans, mikrometeorologiese vertikale profiele, evapotranspirasie, latent hittevloed, waarneembare hittevloed, reënwaterproduktiwiteit.

CHAPTER 1

Introduction

1.1 General

1.1.1 Water scarcity and food security: Global and national prospectives

Global food insecurity remains a serious problem in water scarce areas of arid and semi-arid climates. The world population is likely to increase from 6.5 billion in 2005 to 7.5 and 9.0 billion in 2025 and 2050, respectively. Based on projections of the population growth and the increase in standard of living, there are various views on the rate of increase in food production required to cope with rapidly increasing mouths to be fed (Schultz *et al.*, 2005). The vision of 'Water for Food and Rural Development' indicates the need for doubling the food production over the coming 25 years, whereas the International Food Policy Research Institute (IFPRI) suggests that a doubling in food production would only be required in the forthcoming 50 years (Schultz *et al.*, 2005), whichever is true, food production must increase.

Achieving food security involves increasing access to food and increasing agricultural production. The majority of the world's population live in emerging and least developed countries where roughly 80% of poor people depend on agriculture for their livelihood (Hatibu, 2003; FAO, 2007). Dryland crop production contributes 95% of the food production in sub-Sahara Africa. There may be 130 million poor subsistence farmers in sub-Saharan Africa and a substantial proportion depend on maize to a large extent as basic staple food (Schultz *et al.*, 2005). According to FAO Report on the State of Food Insecurity in the World (FAO, 2000), about 800 million people in developing countries do not have sufficient food. Therefore, optimal utilization of the natural resources, water and soil, is critical in order to be able to maintain more sustainable food production practices.

Food production in semi-arid areas, principally depends on availability of water. Future needs of water for food are extremely high and up-to-date water management systems will be required at various scales. In different regions of the world, depending on local climatic and other factors, different types of water management with different levels of services will be appropriate (Schultz, 2001; 2003). For instance, in-field rainwater harvesting (IRWH), based on the collection and concentration of surface runoff in the field for cultivation, has been practiced in different parts of the world for thousands of years (Reij *et al.,* 1988). Rainwater harvesting, which collects runoff from short slopes, is especially useful in arid and semi-arid regions, where irrigation water is not available or too costly to use (Boers *et al.,* 1986). Therefore, promotion of improved rainwater management, which includes, for example, rainwater capture and conservation, use of mulch cover and soil improvement will be important in order to reduce rural poverty and to ensure food security.

In South Africa, as in developing countries, levels and incidence of poverty tend to be disproportionately high amongst the rural population. The Development Bank of South Africa (DBSA, 1993) estimated that more than 50% of the population of South Africa live below the poverty line. The poorest of rural households mostly live in semi-arid and arid areas and rely heavily on dryland crop production for their livelihoods, often farming on marginal and fragile soils. In dry areas, lack of adequate water poses a major constraint to increasing agricultural production and attempts to develop other economic activities (Twomlow *et al.,* 2006). However, many agricultural scientists agree that with the use of appropriate production techniques, especially those that encourage conservation of water and soil resources, it is possible to increase and sustain agricultural output in semi-arid areas (Hatibu *et al*., 2002). Therefore, the adoption by farmers of agricultural practices that ensure efficient rainfall utilization for dryland production of a wide variety of crops is essential for agronomic, economic and social sustainability. To improve precipitation use efficiency (PUE) it is therefore necessary to adopt water conservation production techniques (Hensley and Snyman, 1991).

In most arid and semi-arid climates, the common phenomenon of low precipitation is aggravated by high evaporative demand of the atmosphere. Schulze (2006) showed an increase in annual rainfall from less than 125 mm along the arid west coast to more than 800 mm on the eastern seaboard of South Africa (Fig. 1.1). The low mean annual rainfall (P, mm $year^{-1}$) is associated with a high mean annual potential evapotranspiration (ET_{pot}, mm) resulting in more than 80% of the country having semi-arid and arid climates (Bennie and Hensley, 2001; Schulze and Maharaj, 2006). These zones can be further divided into winter and summer rainfall regions. At least one third of the country, particularly the central and north-western portion, has less than 400 mm of rain (P) annually. Most of the dryland crop production occurs in the semi-arid zones where the aridity indices (P/ET_{pot}) vary between 0.20 and 0.50. This inadequate rainfall is the main reason for the relatively small portion of South Africa considered to be suitable for rainfed crop production (Bennie and Hensley, 2001).

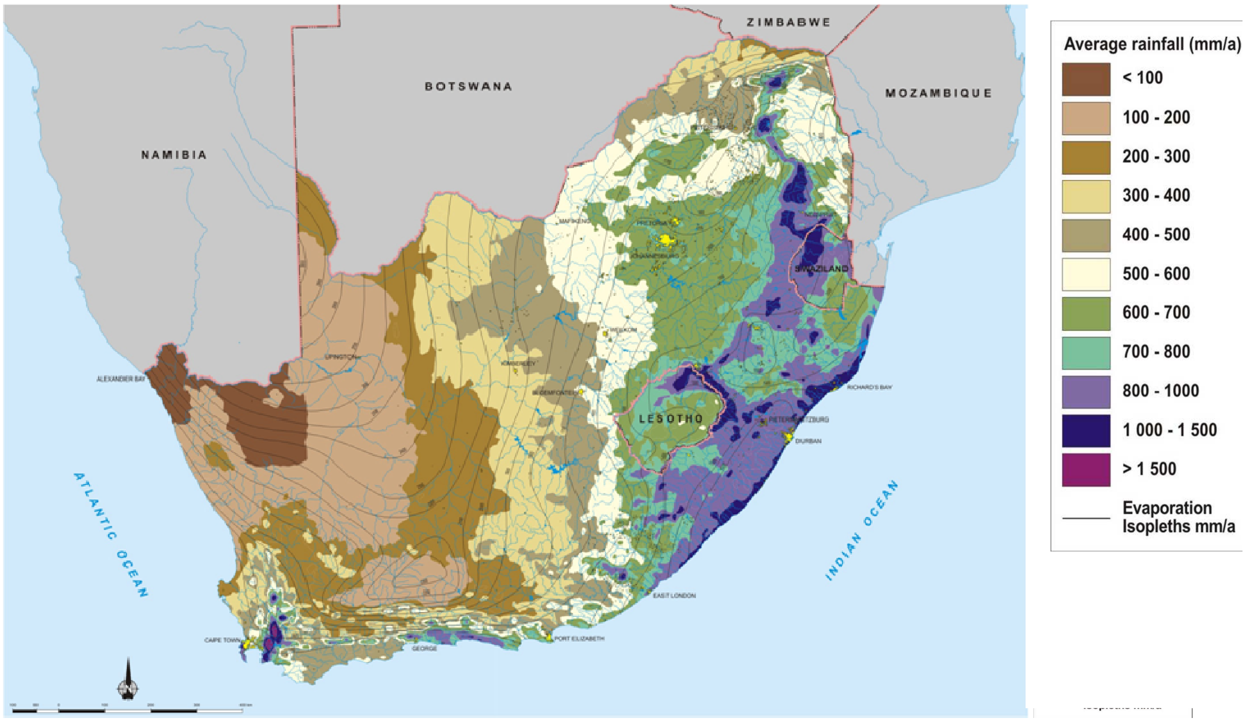


Figure 1.1 Mean annual rainfall (mm) and mean annual evaporation isopleths (mm) for South Africa (Schulze and Lynch, 2006).

In order to sustain the crop production in arid and semi-arid areas, one needs to rely on alternative and manageable conservation techniques that emphasize the optimum utilization of resources. Amongst various water conservation techniques, IRWH is seen as having potential for increasing available resources (in particular radiation and water) for successful crop production. The IRWH technique as proposed by Hensley *et al.* (2000) has been shown to improve maize yield on some benchmark ecotopes in South Africa. On the basis of water and energy balance studies about effective use of resources in a sustainable manner, the technique of IRWH can increase crop yield and decrease production risk under semi-arid conditions.

1.1.2 Water conservation in the context of rainwater harvesting

Rainwater harvesting (RWH) is an age old practice used in water scarce rainfed crop production areas. The primary objective of rainwater harvesting systems in terms of water conservation is to facilitate “runoff farming” (van Rensburg *et al.*, 2005). Hence, water conservation practices contribute in reducing erosion; improve soil quality and increasing PUE. Stroosnijder (2003) further claims that in semi-arid Africa water conservation can easily double PUE thus contributing to food security.

In the semi-arid climate zone the most limiting resource is water. Rainwater harvesting was practiced to provide additional water for crops with insufficient rainfall for optimum yield. It involves collecting rainwater from an area which is not in use and directing it to an area used for production, i.e. to an area where in most cases a crop is grown. Oweis *et al.* (2001) defined RWH simply as “the process of concentrating precipitation through runoff and storing it for beneficial use”. One way of increasing rainwater productivity (RWP) and decreasing production risk in dry areas, is through water harvesting. The IRWH technique (IRWH) as described by Hensley *et al.* (2000) (Fig. 1.2) showed potential in a semi-arid area of South Africa. The main objective of this technique is to maximize RWP, and it is also referred to as “mini-catchment runoff farming” by other authors (Owies *et al.*, 1999).

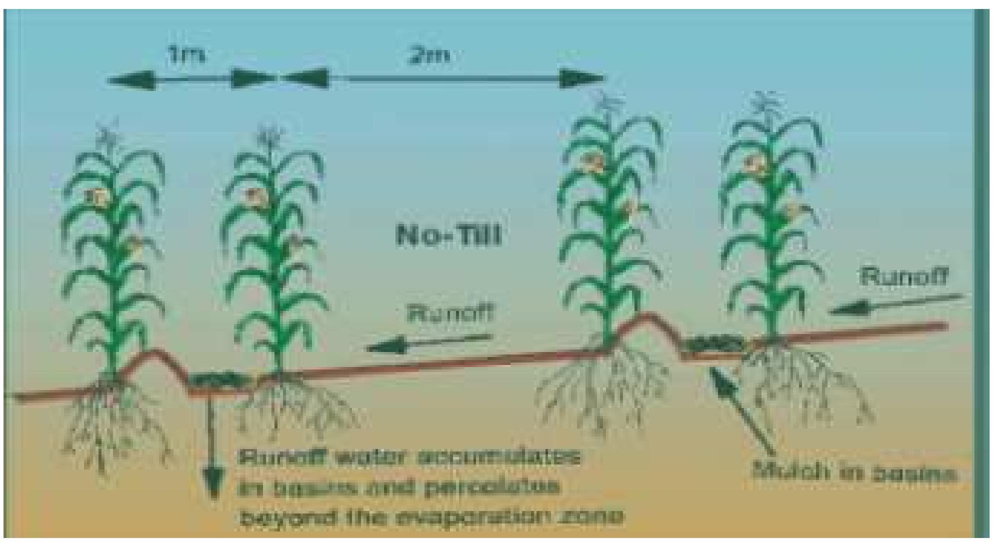


Figure 1.2 A diagrammatic layout of the IRWH-technique, showing the 2 m width runoff strips (catchment) and 1 m width basin strip (collection area) modified as micro basins (Botha, 2006).

This innovative water conservation technique has the potential to eliminate runoff from the field and reduce soil evaporation considerably, resulting in potentially increased yields due to increased plant available water. The technique consists of promoting runoff on a 2 m wide strip between alternate crop rows, and storing runoff water in soil profile under the basins between the tramline rows. The IRWH technique is specifically suited to many ecotopes around South Africa and in other countries with arid and semi-arid areas. According to Kahinda *et al*. (2008) based on the soil and topographic physical layers, suitable IRWH areas (categorised as high and very high), were found to cover about 25% of South Africa. These include large areas of Free State, North West and Limpopo as well as parts of Eastern Cape, KwaZulu-Natal and Mpumalanga (Kahinda *et al*., 2008). Therefore, over the last few decades attention has been paid to traditional techniques of water harvesting, especially in dryland crop production (Boers and Ben-Asher, 1982; Hensley *et al.,* 2000; van Rensburg *et al*., 2005; Botha, 2006; Anderson, 2007).

Several studies were conducted on the biophysical sustainability of the IRWH technique on different soils and under different climatic conditions, as listed in selected research reports in Appendix 1.1. For example, Botha (2006) evaluated the performance of the IRWH on four ecotopes with clay, fine sandy clay, clay loam and fine sandy loam soils (45, 38, 37 and 17% clay content, respectively) in the central Free State and concluded that the IRWH technique is sustainable and superior to mouldboard ploughing conventional tillage. Yields of maize and sunflower were between 30 and 50% higher than that under conventional practices. He explained that yield advantages could be attributed to total stoppage of ex-field runoff and reduction of evaporation from the soil surface, supplying more water for transpiration. The enhancement of in-field runoff towards the basins induces or increases water availability to crops, thereby increasing rainwater productivity (RWP) significantly (Botha, 2006).

However, the IRWH technique was mainly field tested on clay soils, with a fixed runoff strip length (2m) to basin area (1m) arrangement, and this may not be a sufficiently rigorous evaluation compared to the existing production system. Therefore, in this study different sizes of runoff to basin area ratio have been practiced on a 2000 mm deep fine sandy loam Bainsvlei soil at the Kenilworth experimental farm. In addition to the investigation of water balance and rainwater productivity, a study of climatic variable profiles and energy fluxes from micrometeorological measurements for a maize field under IRWH is also included.

1.1.3 Problem description

Dryland farming in arid and semi-arid cropping systems, in the absence of irrigation, is characterized by rainfall which is both low and unreliable; therefore, farmers have turned to rainwater harvesting. However, a lack of technical knowledge to choose the best configuration has been identified as one of the primary factors preventing wide-spread adoption of rainwater harvesting amongst resource-poor farmers in semi-arid and arid areas (Rockstrom, 2000; Hatibu *et al.*, 2002). In the system of RWH, farmers also use other cultural practices like shelter belts, intercropping and mulching to ensure production despite environmental constraints (Stigter and Weiss, 1986). Amongst other factors, the technical research of mulch combinations with IRWH technique have been discussed in detail (van Rensburg *et al*., 2002; Botha *et al.*, 2003), but it seems that the full agronomic potential has not yet been realised.

The know-how of energy balance partitioning over IRWH for a range of runoff sizes has not been assessed to enable optimum utilization of resources in semi-arid areas. Furthermore, in many cases agronomical and biophysical properties of such techniques (e.g. IRWH) are well understood together with the ability to increase yield. This promising technique of IRWH is also expanding into large portions of marginal land in the Free State (Botha *et al.,* 2003). However, widespread understanding and diversified knowledge of IRWH has not yet been comprehensively appraised and needs more research - such as:

(i) The proportion of runoff harvested water (run-on) needed to increase maize production according to different sizes or lengths of runoff strips, with various mulch rates on typical sandy loam soils;

(ii) The influence of mulching and shading on soil evaporation under a maize crop for different runoff to basin area ratios. This leads one to investigate changes in plant available water capacity (PAWC) and a detailed evaluation of soil water balance components. These studies will look into detail on partitioning of evaporation from the crop canopy (Ev) and evaporation of soil water (Es) from different sections of basin and runoff areas.

(iii) Moreover, the majority of IRWH studies did not include any micrometeorological measurements - firstly, to assess air temperature, water vapour and wind speed profiles and vertical gradients within and above maize canopy; secondly, to clarify energy balance components and energy available for evaporation in wide compared to narrow runoff strip configurations.

Therefore, this research will contribute towards the understanding of the utilisation of soil water and climatic resources under IRWH technique specifically, and in broad sense in other water conservation approaches. This research study will also be beneficial for small-scale resource-poor farmers in terms of clarifying risk and promoting higher sustainable yield by efficiently using variable climatic resources in semi-arid areas.

1.2 Background

1.2.1 Crop production and climate of the Free State

Out of the total land surface area of South Africa (122.8 million ha), the Free State occupies 12.9 million ha. However, the potential arable area of the Free State Province covers only approximately 3.82 million ha, while natural veld and grazing cover approximately 8.7 million ha (South Africa Yearbook, 2002/03). It is estimated that of the arable land, 8% is of very low, 49% of low and 43% of medium agricultural potential (Hensley *et al.,* 2006). Field crops contributed an average of 54.3% to gross agricultural income for years 1983, 1988, 1991 and 1993 (Department of Agriculture - Free State Province, 1996).

Small-scale farmers occupy large areas of the Free State Province of South Africa (Department of Agriculture - Free State, 1996), but they do not all experience food security because most of the area is marginal for crop production. There are three reasons for this (Fig. 1.3):

- (i) low and erratic rainfall amounting to mean of 543 mm per annum;
- (ii) a corresponding high evaporative demand of 2198 mm per annum;
- (iii) dominantly duplex and clay soils on which the precipitation use efficiency (PUE) is low due to high runoff and evaporation losses (Hensley *et al.,* 2000).

As a result, in the Free State the most important factor limiting agricultural production is the availability of water (Eloff, 1984).

Crop production in the Free State generally contributes approximately 34% to South Africa's maize production. Statistics obtained from the Department of Agriculture - Free State (2006) revealed that Free State agriculture contributes on average 4.6% and 9.2% of gross geographical product and agricultural production in South Africa. Proper knowledge of agricultural potential and a good understanding of characteristics of specific ecotopes is therefore of utmost importance for optimum and sustainable resource utilization in practicing IRWH.

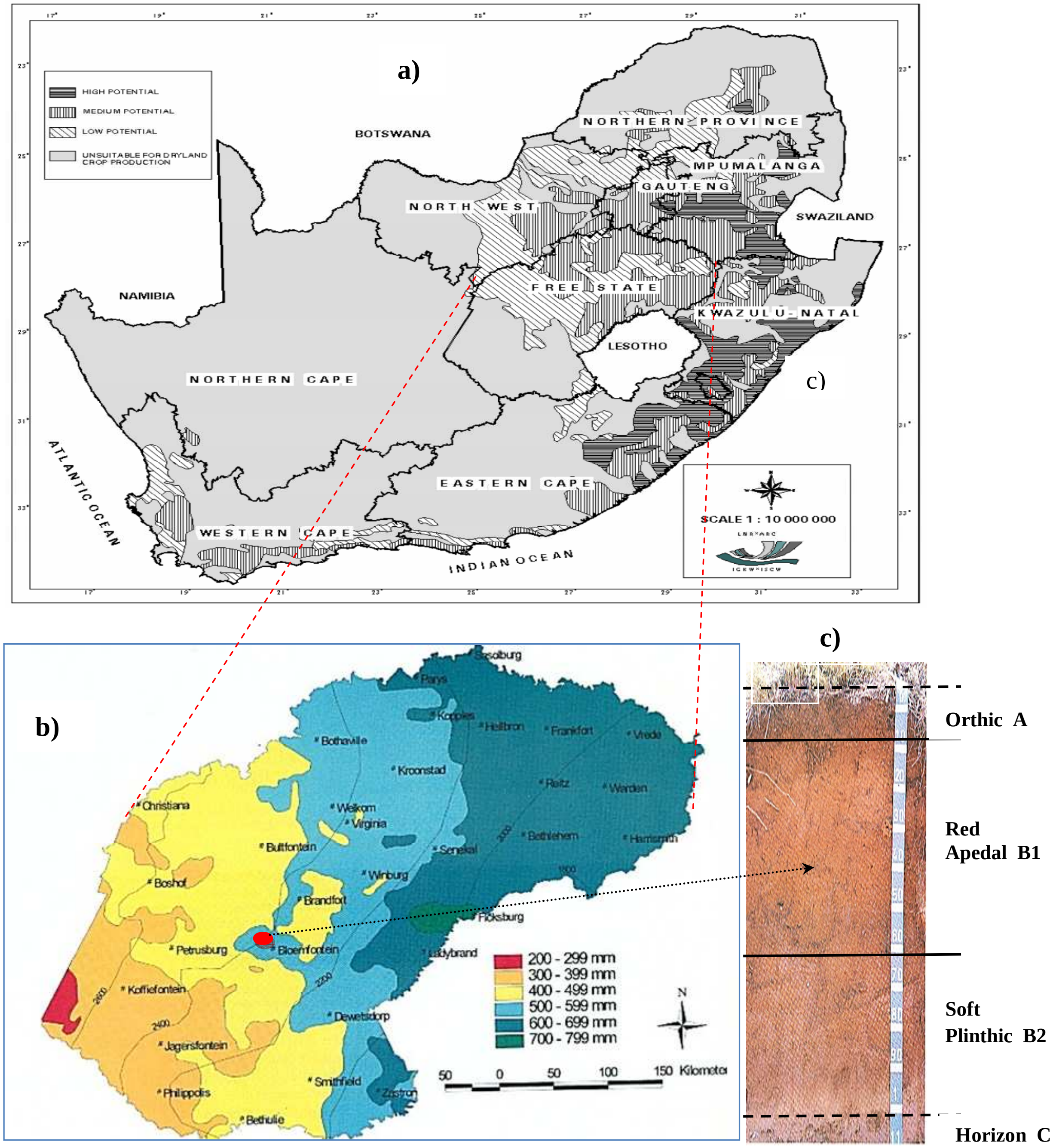


Figure 1.3 Map showing a) generalized crop potential of South Africa (Beukes *et al*., 2004); b) mean annual rainfall and evaporation isolines as A-pan equivalent (Schulze, 1997) in the Free State and c) Bainsvlei Form-Bv, soil profile of the experimental site (Kenilworth Bainsvlei ecotope) (Soil Classification Working Group, 1991).

The rainfall in Free State varies considerably from west to east and has approximate annual rainfall of 200 – 800 mm from dry semi-arid to dry sub-humid zones (Fig. 1.3b). Thus, the climate of the Free State has a wide precipitation range and characterized with water deficit areas and the daily mean potential evaporation levels are very high ranging from 6 – 8 mm d^{-1} (Schulze and Lynch, 2006) and would be much higher during summer. In the central part of Free State, rainfall is highly erratic and some rain falls as intensive convective storms with extreme spatial and temporal rainfall variability. As a result the semi-arid part of the Free State has a risk for annual drought and inter-annual dry spells. This has a serious effect on crop yield in particular during water sensitive stages, e.g., at flowering / tasseling. According to the aridity index (AI), as defined by United Nations Environmental Programme (Middleton and Thomas, 1992), criteria for bioclimatic zoning, the climate of the Free State is categorized as semi-arid (Hensley *et al.,* 2006). Despite this the province is one of the major contributors of agricultural production in South Africa.

1.2.2 Characteristics of the Kenilworth Bainsvlei ecotope

An ecotope is "a class of land defined in terms of its macro-climate, soil and soil surface / topography characteristics" (MacVicar *et al.*, 1974; as cited by Hensley *et al.*, 2000); therefore ecotopes with similar characteristics are generally considered to have homogeneous climate, soil and topography (Hensley *et al.*, 1997). The study area (Kenilworth Bainsvlei ecotope**)** is located in the Free State Province in the 400-550 mm rainfall region (Fig 1.3b), an area of low potential for crop production (Fig. 1.3a). In the past, crop production in the Free State Province has generally been low in areas with mean annual rainfall < 500 mm, effective rooting depth of < 600 mm and clay content of < 10 % and > 35 % (Eloff, 1984).

The characteristics of the Kenilworth Bainsvlei ecotope are associated with high evaporative demand and relatively low and erratic rainfall. Topographic description of plots is having < 1% slope falling Northward. The basic soil morphological property, according to the Soil Classification Working Group (1991), is reddish brown in colour (*Amalia family*) with a fine sandy loam texture, thus classified as a Bainsvlei form, and it has lower soil crust formation than clay soils.

Soil texture and structure, bulk and particle densities and porosity are the major soil physical properties that determine the extent of the water storage capacity of soil, although, probably, the single most important parameter is texture. All layers of the Bainsvlei soil have very low silt contents, ranging from 4 to 5.3%, similar sand contents (>67% in each case) and clay contents of between 8 and 22%. Generally bulk density is fairly uniform down the soil profile, ranging from 1.65 to 1.68 Mg m^{-3}. The massive structure is relatively uniform throughout the profile as the Bainsvlei form soil profile can be described as being relatively homogenous with depth. Chimungu (2009) summarized the homogeneity of the different horizons of Kenilworth Bainsvlei soil in terms of water contents at different suctions for different horizons. The results showed that at different suction, particle size distribution was the dominant factor that controls water retention with a slight variation in clay content and bulk density down the profile (Chimungu, 2009). Due to the soil profile ability to hold rainwater, this type of soil can play a significant role in dryland farming, so it would allow for plant growth over a typically hot summer when evaporation exceeds rainfall.

Soil profiles with a specific sequence of diagnostic horizons are considered to have distinctive characteristics for crop production. The Bainsvlei soil form is a very suitable agricultural soil for conservation tillage in this semi-arid climate as the profile is deep (2000 mm) and drains freely while the plinthic horizon dams water within the lower part of the profile, which is within range of plant roots during frequent dry spells (Bennie *et al.*, 1994). The efforts of agricultural water management (for example IRWH) have primarily focused on maximizing rainfall infiltration through in-field runoff. This helps resolve the challenge of how to cope with dry spells, which cause short periods of water stress during crop growth. Thus, in the Kenilworth Bainsvlei ecotope, the factors which play a dominant role in applying IRWH are the high infiltration capacity of A (orthic) and B1 (red apedal) and slow flow through B2 (soft plinthic) soil profile horizons (Fig. 1.3c).

1.3 Scientific justifications

1.3.1 Rainfall-runoff processes

As runoff is an important water balance component in arid and semi-arid areas, a critical question in rainfall - runoff processes is how much runoff water is generated in response to the amount, intensity and duration of a rainstorm. Under practical dryland crop production conditions, the theoretical relationship relating daily rainfall to rainfall intensity and runoff is of great importance as it is fundamental to the success of the IRWH technique. Hensley *et al.* (2000) described runoff as of paramount influence in optimizing rainfall efficiency for dryland crop production. Hence, to better understanding the rainfall-runoff processes in IRWH, one needs a simple quantitative understanding of the interface between meteorology and soil water.

The long-term rainfall intensity data to predict the amount of runoff water potentially available and channelled onto productive land to be used for crop production is a key factor in describing the rainfall-runoff process. In this matter, Walker and Tsubo (2003a) tested various theoretical relationships and developed a method to generate rainfall intensity data from historical records of daily rainfall at selected bench mark ecotopes and to predict expected amount of runoff. Different studies also show that there are wide variations in the relationship between rainfall and runoff amounts. Hensley *et al.* (2000) used a simple method of estimating runoff from rainfall by linear regression analysis. Linsley *et al.* (1982) showed an infiltration index system and Connolly (1998) used another rainfall excess model. As a result, several models of water harvesting from rainfall - runoff – water yield processes have been developed.

For instance, Young *et al.* (2002) introduced the comprehensive model simulator “Parched-Thirst”. This simulator generates 5 minute rainfall intensity from incomplete long-term rainfall data and estimates runoff and then predicts crop growth and yield. Along with rainfall intensity, infiltration capacity of the particular soil is also critical to facilitate the calculation of water flow. Morin and Cluff (1980) determined that a decrease in the infiltration rate was caused by the formation of a crust due to direct impact of rain drops on the soil surface, increasing overland flow. Thus, the process of rainfall - runoff for fine sandy loam soils of Kenilworth Bainsvlei ecotope site is different from high clay content soils. Furthermore, applications of various organic mulch rates on runoff strip sections also influences infiltration capacity of the soil. These have direct or indirect effects on plant available water of root zone and on PUE.

1.3.2 Rainfall canopy interception

The canopy rainfall interception processes plays an important role in water balance physical processes in both sparse and densely planted crops. During a rainfall event, water either penetrates the canopy falling directly to the soil surface or is intercepted by the canopy then some falls to the soil surface. The capacity of a vegetative surface or canopy to intercept rain and temporally store water is of great importance. As such rainfall interception and its subsequent evaporation constitute a net loss to the system, and can be considerable amounts under certain conditions. During precipitation, interception by a canopy is recognized as a component in the hydrologic cycle that can affect the water balance of a soil by altering the amount that infiltrates into the soil (Bristow *et al.*, 1986). In short, canopy interception is the amount of water remaining on leaf and stem surfaces of the plant after through fall and stem flow (Dunne and Leopold, 1978). The process depends strongly on:

(i) vegetation type and stage of development, which can be characterized by leaf area index (LAI) and
(ii) intensity, duration and frequency of rainstorms.

The concept of rainfall interception capacity of canopy structures was considered as an initial process before it reaches the soil surface or mulch covering. Once precipitation water reaches the soil surface the process of interception by the canopy is complete and the processes of runoff or infiltration begin. The canopy structure at different growing stages is therefore extremely important to interception and resulting amount available for infiltration and runoff.

1.3.3 Soil water balance and productivity

For dryland crop production in semi-arid areas on soils without a watertable, without significant surface or internal lateral water movement, and for a specific period, a simplified water balance equation can be written as follows after (Bennie *et al.*, 1994):

$$Ev = (P \pm \Delta S + R_{on}) - (R_{off} + Es + D) \qquad \textbf{1.1}$$

where Ev = transpiration (mm), P = rainfall (mm), ΔS = change in water stored in root zone (mm), Es = evaporation from soil (mm), R_{on} and R_{off} = run-on and runoff (mm) and D = deep drainage.

Figure 1.4 is a schematic representation of amount and fluxes in the soil water balance, defining boundary conditions of the whole physical environment. For example, the volume of soil, per unit surface area, and depth ranging from the soil surface (z = 0) to the bottom of the root zone (z = L), where z (m) is vertical position coordinate. As water flux is considered only in the z-direction, in, a unidirectional approach, which is a simplification that is best valid when the soil is fairly homogeneous and without considering lateral flow. Water corresponds to amounts of water that flow per unit of cross-sectional area and per unit of time (mm d^{-1}). They are vectors, assumed positive when entering the volume element (gain), and negative when leaving (loss).

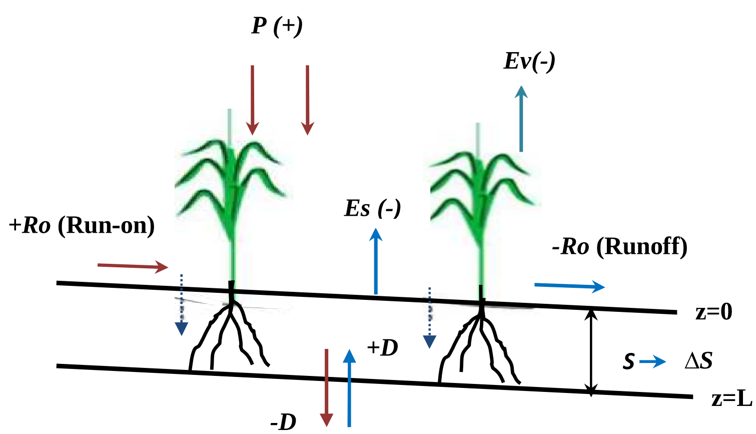


Figure 1.4 Schematic representation of the water fluxes that compose the water balance (Reichardt *et al.,* 2007), where, z = 0 and z = L represent the root zone from top surface to bottom of profile and +D and -D show the upward and downward soil water process.

At the upper boundary, soil surface (z = 0), rainfall is considered as a gain; evaporation, transpiration, or evapotranspiration (ET) and runoff (Ro) are losses. In some cases, runoff can be the run-on water flow (+*Ro)* into another area considered for the water balance, and then runoff becomes positive. At the lower soil boundary, bottom of root zone (z = L), soil water flux can be a gain (upward, +D) into the root zone called capillary flow, or a loss (downward, -D) representing deep drainage (D) component. The change in soil water storage ΔS is the result of a arithmetic balance, being positive when the profile has a net gain of water, and negative for a net loss during the specific time period.

Deficit soil water is a common phenomenon for cereal crops grown in arid and semi-arid regions due to low and erratic rainfall (Biamah *et al.,* 1993). The low precipitation received is greatly influenced by high evaporative demand of the atmosphere in these regions. Different studies have shown negative consequences of water deficit in semi-arid ecotopes, as crops need water in varying amounts at different stages of their growth period (Russhton *et al.,* 2006; Passioura, 2006). Generally, most crops have four different main stages which require different amounts of water, *viz*. initiation, development, maturity and senescence (Allen *et al.*, 1998).

The amount of water that is needed by crops during their whole growing season is known as crop water requirement or in the past called consumptive use (Allen *et al.*, 1998). It comprises the amount transpired (Ev) by plants plus that which evaporates (Es) from the soil surface (i.e. together ET). Many scientists have reported relationships between crop yield and water use expressed as transpiration or evapotranspiration, however they discovered that water use by plants for Ev is directly related to the total dry matter yield of the crop (De Wit *et al.,* 1978; Ogindo and Walker, 2004; Passioura, 2006; Haka, 2010). In order for crops to produce optimum dry matter, they need to receive the required amount of water during their growing period, and it also needs to be suitably distributed through the growth stages. Water deficit due to different reasons, particularly at critical growth stages, will cause a reduction in total dry matter accumulated (Hsiao and Acevedo, 1974; Azam-Ali *et al.,* 1989; Haka, 2010).

Therefore, improving the soil water content in the root zone using different water conservation techniques (e.g. IRWH) can promote increased crop yield. In addition, by improving the available soil water by using different cultural practices, such as mulching, fertilization, optimum plant density etc., it is possible to maximize the utilization of semi-arid ecotopes resources. In this regard, quantification of the soil water balance is of significant importance in understanding efficient water utilization under IRWH system.

1.3.4 Effect of mulch on water use and production

Mulching is the practice of leaving or applying dead plant material as a covering on the soil surface, and has advantages in limiting soil erosion by runoff, decreasing water loss by evaporation and changing soil temperature (Stigter and Weiss, 1986, Nhlabathi, 2010). It also shields the soil surface from solar radiation (Enz *et al.,* 1988; van Rensburg, 2010). Mulch is used in arid or semi-arid and frigid regions for conserving soil heat and water content to improve crop growth and productivity (Flerchinger and Clark, 2003). Mulching in the IRWH technique helps in sustaining the system by reducing the sedimentation rates that could affect the storage capacity of the basin area. Botha *et al.* (2006) showed that most soil transportation occurred on the bare surface treatments and concluded that mulch on the runoff area played a beneficial role in terms of sustainability regarding surface storage capacity of the basin.

In general, the influence of mulch cover on the runoff strips can be considered as modifying soil temperature and water content of the soil. This effect of mulch arises from changes in proportion of solar radiation energy intercepted, sensible heat transferred to the atmosphere and a lower conductance of heat into the soil. Consequently, latent heat energy is reduced and sensible heat flux increased under high mulch cover compared to amounts over low mulch or a bare soil surface (Lie *et al.,* 2004). Reducing evaporation from a crop field through mulching enhances both productivity and water use efficiency (Lie *et al.,* 2004) and utilizes the conserved water for higher transpiration and improved yield (Sarkar and Singh, 2007). This agrees with the approach proposed by Passioura (2006) and is expected to increase the water efficiency of grain yield.

Therefore, different mulch rates used in the IRWH technique may alter the utilization of climatic resources at the soil-plant canopy interface and change crop productivity. In this study, at arrange of mulch rates on different runoff strip lengths was investigated as a good cultural management strategy to promote effective utilization of climatic resources without significant decrease in maize yield for semi-arid areas.

1.3.5 Micrometeorological characteristics in plant canopy

1.3.5.1 Profiles and fluxes within and above crop canopy

Turbulence generated within a plant canopy is a much more complex process than that over a flat bare surface or within a homogeneous boundary layer above a crop canopy. Fluxes of momentum and heat in the atmosphere surface layer are generally described with non-dimensional wind, temperature and water vapour gradients using Monin Obukhov (M-O) Similarity Theory (Monin and Obukhov, 1954). This interesting area in micrometeorology is concerned with the atmospheric environment contribution of energy (Arya, 2001), and suggests plausible functional relationships both within and above crop canopy and in the interactions with the bulk atmosphere.

Vertical exchange of heat and water vapour are primarily through turbulent motions in the plenary boundary layer. Therefore, the primary objective of various micrometeorological studies involving crop canopies has been a better understanding of the processes of momentum, heat and mass exchange between the atmosphere and the biological active canopy zone. These exchanges influence the local microclimate in which plants grow. For example, in rainfed maize production, it can be used to verify and characterize the vertical profiles of wind, temperature and relative humidity as an important step towards generating reliable heat and water vapour flux estimations. This is done in order to evaluate alternative agronomic management practices from an energy and water balance point of view.

The canopy vertical profile gradients illustrate the physical processes within and above the canopy for heat and water vapour transfer (Fig. 1.5). Horton *et al.* (1984) and Horton (1989) followed specific initial boundary conditions to describe soil heat and water flow in the presence of row crops. Heat and water flow are assumed to be negligible in the direction along the rows. The *x*-dimension is chosen to be horizontally perpendicular to the plant rows with left ($x=0$) and right ($x=L_1$) (Fig. 1.5) with a boundary occurring at the centre of two adjacent rows. The *z*-dimension is vertical and exits from the soil surface ($z=0$) to an arbitrary selected crop height ($z=L_2=hc$) and the y-dimension is parallel to rows. Different row crops cause non-uniform soil surface shading; thus solar irradiance and subsequent surface energy partitioning and transfer are directly affected by a crop canopy. The shaded and unshaded portions of the ground between plant rows are used when determining the exchange of energy at the various surface positions. These numerical procedures therefore have been considered to provide a conceptually reasonable prediction of surface partitioning of heat and water flux within various sizes of row crop canopies.

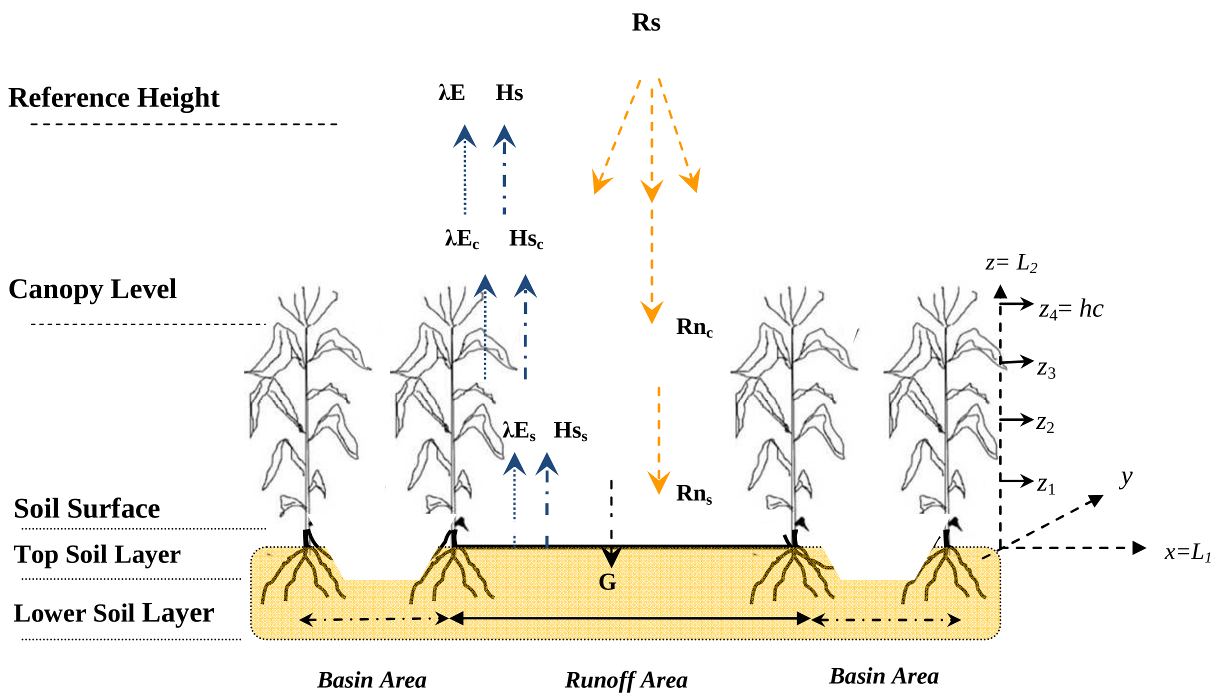


Figure 1.5 Schematic representation of energy fluxes as energy balance components in the system of in-field rainwater harvesting. (Symbols explained in text). On the right side, an illustration for canopy profile with horizontal *x*-dimension perpendicular to plant rows, vertical canopy profile z-dimension and *y*-dimension is parallel to plants rows, *z=hc* is canopy height.

1.3.5.2 Energy balance components

Understanding heat and water vapour fluxes within and above a plant canopy can assist in explaining the microclimate characteristics and their effect on plant processes, for improved management practices in rainfed agriculture (Xiao *et al.*, 2006). The sun supplies virtually all the energy received by the earth, which drives the process of photosynthesis, heating both soil, and air and for evaporation. The absorption of energy at the surfaces of canopy elements and soil and its partitioning into sensible and latent heat involve a number of interacting processes. Jury and Horton (2004) mentioned a one-dimensional steady-state energy balance at the soil surface in canopy as follows:

Net heat energy arriving at surface - Net heat energy leaving surface = 0 **1.2**

A simplified form of the energy balance equation in the soil or in plant canopies has been used to assess components of energy. The process occurs predominantly by turbulent convection (bulk flow) of air, latent heat flux by vaporization and soil heat flux by conduction as follows:

$$Rn - Hs - LE - G = 0 \quad \textbf{1.3}$$

where Rn is the net radiation, Hs is the sensible heat flux, LE is the latent heat flux and G is the soil heat flux. All energy balance components in units of W m^{-2}.

Energy balance models combine these four fluxes, as described by Shuttleworth and Wallace (1985) and Choudhury and Monteith (1988), for a crop canopy or plant community, fluxes in different layers such as, first layer extending from a reference height above the vegetation (canopy) to the sink of momentum within the top of the canopy, a second layer between the canopy and soil surface and a third layer correspond to the top layer of soil (Fig. 1.5).

The energy balance distributes net radiation into sensible (Hs) and latent heat (LE) and soil heat flux (G) through the soil-canopy system. The total latent heat is the sum from canopy (LE_c) and from soil surface (LE_s). Similarly, sensible heat is calculated as sum of sensible heat from canopy (Hs_c) and from soil surface (Hs_s). The total net radiation results from the balance of all incoming and outgoing radiation at the canopy (Rn_c) and soil (Rn_s) levels and is given by $Rn = Rn_c + Rn_s$. Horizontal gradients of potential fluxes and physical and biochemical energy storage terms in the canopy/residue/soil system are considered to be negligible in this representation.

However, the flux of solar radiation reaching the canopy and soil surface under different row widths varies according to a range of conditions (Allen *et al.*, 1998). The amount of solar radiation received and reflected by the canopy and soil surface strongly depends on the row width and solar zenith angle, according to the latitude and time of year. The combined effect of absorbed and reflected radiation has great influence on the partitioning of latent and sensible heat over of different runoff strip lengths compared to the basin area with different plant densities. As the climate becomes drier and more variable it is important to know how crops will affect and be affected by the heat and water balance. Crop canopies affect the soil energy balance by having a different surface albedo, decreasing the depth of penetration of radiation through canopy, increasing the removal of latent heat by evapotranspiration and decreasing the rate of heat loss from the soil surface due to different surface temperatures. Thus, with the IRWH tillage system, the main impact of surface on soil environmental conditions is through the effects on surface temperature and soil water content and their complex interaction with the surface energy balance.

1.4 Research goal, objectives and questions

In line with the problem statement above, the following overall goal, specific objectives and research questions have been addressed in this study.

1.4.1 Overall goal of the study

To contribute to the on-going research on the technique of in-field rainwater harvesting by investigating the atmospheric component, aimed at adequately understanding the water and energy balance processes of a maize crop under IRWH, so as to promote better production levels in a sustainable manner. Therefore, the main aims of the research were:

(i) to establish the effect of a range of runoff to basin area ratios, with a range of mulching levels, on the soil water balance and maize production; and

(ii) to quantify the energy and water transfer within the crop canopies of different runoff to basin area ratios using micrometeorological methods.

1.4.2 Specific objectives of each chapter

To achieve these aims and to make a contribution towards understanding sustainable maize crop production in semi-arid areas of the Free State, a number of objectives were set for research carried out in two cropping seasons, 2007/08 and 2008/09. The specific objectives were:

- to quantify the effect of surface properties (various runoff strip lengths (RSL) and mulch levels (ML) in the IRWH tillage technique during the maize growing season on a Bainsvlei Kenilworth ecotope (Ch. 3);
- to derive a simple empirical model to predict in-field runoff based on rainfall event characteristics and cultural practices for IRWH system (Ch. 3);
- to evaluate rainfall canopy interception (RCI) under different runoff strip lengths of IRWH (Ch. 4);
- to quantify the effect of surface treatments (RSL and ML) on runoff-rainfall (RR) ratio (Ch. 4);
- to determine the partitioning of rainwater falling on the runoff strips and basins and the fraction of rainwater available to infiltrate into the soil system of IRWH (Ch. 4);
- to quantify the effect of surface treatments (RSL and ML) on soil evaporation (Ch. 5);

- to conduct a detailed analysis of Es from each 1 m section of IRWH to quantify the effect of crop shading and mulch levels (Ch. 5);
- to evaluate the Ritchie and Stroosnijder models across the basin and runoff sections of IRWH (Ch. 5);
- to develop empirical models to estimate cumulative soil evaporation (∑Es) across the basin and runoff sections beneath a maize canopy as influenced by varying amount of stover mulch (“*dry-mulch*”) and canopy shading (“*green-mulch*”) under the IRWH technique (Ch. 6);
- to quantify the soil water balance components for each surface treatment using the measured rainfall and soil water content; and empirically calculated runoff, run-on and soil water evaporation, therefore being able to calculate the transpiration as a residual (Ch. 7);
- to compare the efficiencies of use and storage of rainfall and productivity of the IRWH system to produce maize grain (Ch. 7);
- to examine and characterize the vertical profiles of temperature, vapour pressure and wind, by comparing wide and narrow runoff strips during different growth stages (Ch. 8)
- to describe relationships between the wind speed (u) versus water vapour pressure (ea) and virtual potential temperature (θv) versus water vapour profiles within a maize canopy under wide and narrow runoff strips (Ch. 8);
- to characterize the vertical profiles of temperature (using virtual potential temperature θv), water vapour pressure (ea) and wind speed (u) within and above a maize canopy for dry and wet conditions in wide and narrow runoff strips (Ch. 9);
- to describe the water vapour pressure deficit (VPD) under different atmospheric and soil surface conditions for wide and narrow runoff strips (Ch. 9);
- to quantify the components of the energy balance; (Ch 10) and
- to compare the available energy so as to estimate ET for a maize crop under IRWH with wide and narrow runoff strip lengths (Ch. 10).

1.4.3 Research questions and hypothesis

The specific questions concern:

(i) What is the optimal runoff to basin area ratio to sustain maize crop yield using IRWH techniques in semi-arid areas of Free State? and

(ii) How do the microclimatic conditions change under wide versus narrow runoff section of IRWH.

This study tests the hypothesis that, within the technique of IRWH there is an optimal runoff to basin area ratio that can maintain a consistent maize production with reduced risk of crop failure under Kenilworth Bainsvlei ecotope.

1.5 Set-up of this thesis

This thesis comprises and discusses a practical and theoretical framework on the basis of both the water and energy balance processes for the IRWH system on the Kenilworth Bainsvlei ecotope. In chapters 3 and 4 the rainfall-runoff relationships from different runoff lengths and mulch rates will be assessed and quantified. Chapters 5 and 6 mainly analyze soil evaporation from microlysimeter measurements and develop empirical models for soil evaporation as influenced by mulch rate with varying amounts of canopy cover or shading at different growth stages in this semi-arid area. Chapter 7 provides an extensive account of the water balance for different runoff lengths with various mulch rate covers to evaluate the productivity of IRWH in terms of its ability to convert rainwater into maize grain yield and dry matter production by minimizing unproductive losses (Es and Ro) and maximizing PUE and RWP.

In Chapter 8, the micrometeorological measurements at different growth stages of maize under IRWH are examined to characterize the profile of meteorological variables within the maize canopy of wide and narrow runoff strips. Chapter 9 assess the relationship of vertical temperature, water vapour and wind speed gradients for both wide and narrow runoff strips, in order to describe profiles and vapour pressure deficit relationships within and above canopy. Chapter 10 focuses on the comparison of energy available for evapotranspiration on wide versus narrow runoff strips by quantifying the energy balance components of a maize crop under the IRWH system. Finally, Chapter11 gives general conclusions and prospects for future research.

CHAPTER 2

Materials and Methods

2.1 Description of the ecotope

The Kenilworth Experiment Farm of the Department of Soil, Crop and Climate Sciences of the University of the Free State is located (Latitude 29^{o}01'S, Longitude 26^{o}09'E, Altitude 1354 m above sea level) near Bloemfontein in the Free State Province of South Africa, 15 km north of the University of the Free State. In 2007 a new IRWH experimental plot was layout to evaluate IRWH with various runoff to basin area ratios and mulching practices on the Kenilworth Bainsvlei ecotope.

2.1.1 Climate

The climatic characteristics of the Kenilworth Bainsvlei ecotope, as in other semi-arid areas, are associated with high evaporative demand and a relatively low and erratic rainfall. Mean monthly climatic data (ARC-ISCW Climate Data Bank) for the Kenilworth Experimental Farm for 10 years up to 2009 is shown in Fig. 2.1. The study area is categorized as a semi-arid climate with mean annual rainfall of 528 mm (std. $\pm$ 155.6 mm) and annual mean of minimum and maximum temperature of 11.0^{o}C and 25.5^{o}C (monthly std. $\pm$0.8 – 2.0^{o}C and $\pm$1.2 – 3.1^{o}C), respectively. The main rain season is from October to April, although some rain also occurs during August, September and May.

Rainfall during December and January is generally erratic and many of the rain events are in the form of thunderstorms with high rainfall intensities. From the long-term climatic data, January, February, March and April receive a large amount of rain, but are accompanied by low evaporative demand. March therefore, has the highest aridity index (AI) with a value of 0.42 although the mean AI of this ecotope is 0.22 (Fig. 2.1a). In winter (May to August), low temperatures are experienced with few occurrences of rain.

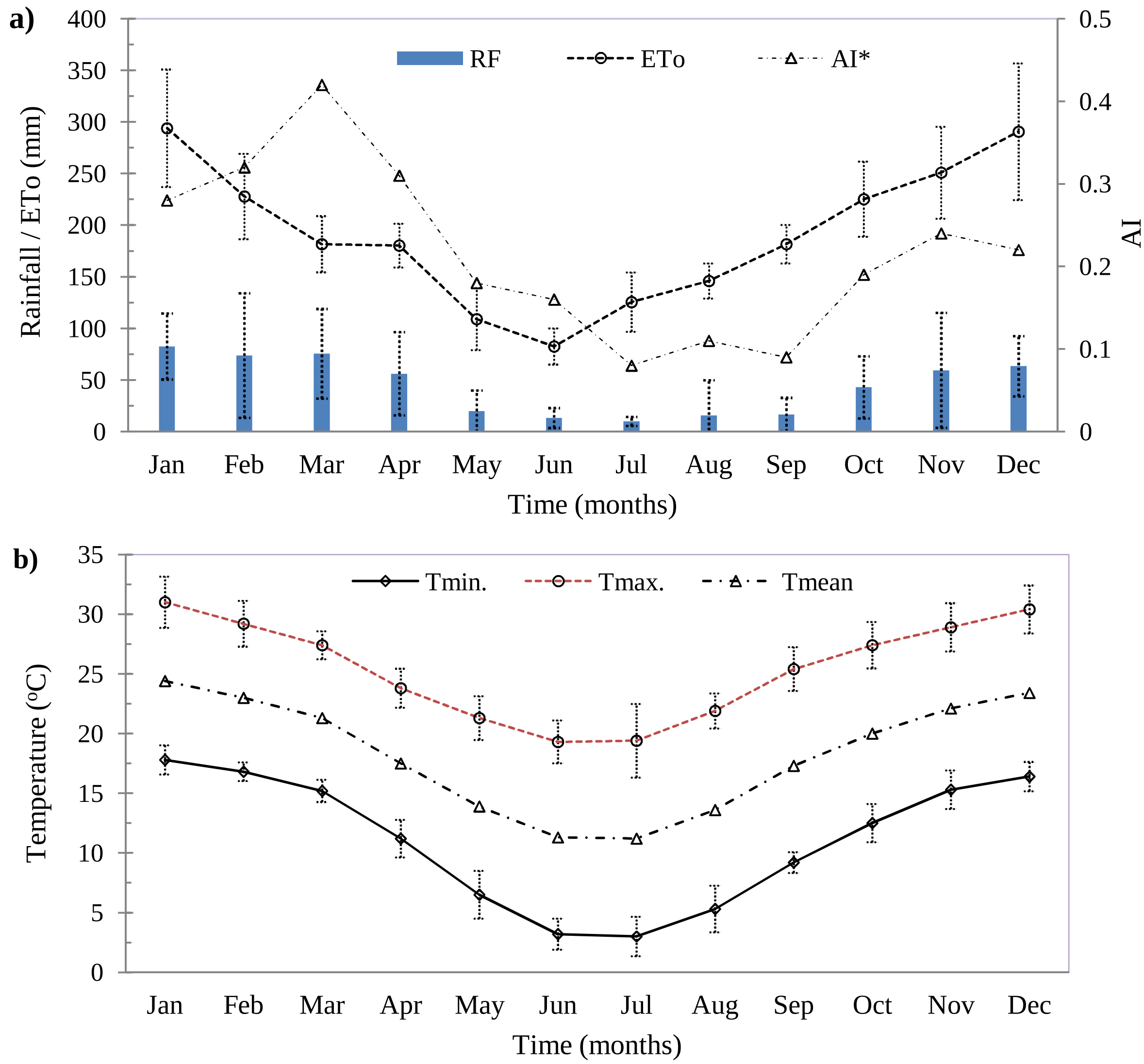


Figure 2.1 (a) Long-term mean monthly rainfall (RF), reference evapotranspiration (ETo Penman-Monteith) and AI; (b) minimum and maximum temperatures climate data from UFS Experimental Farm (Kenilworth site). Data set from 2000-2009, source ARC-ISCW Climate Data Bank. *AI calculated Aridity Index = (RF/ETo).

During the maize growing season (Nov – Apr) the long-term mean rainfall is 350.2 mm with a high reference evapotranspiration of 1451.5 mm. January is the hottest month with a mean maximum temperature of 30.4°C and May is the coolest month of the growing season with a mean minimum temperature of 6.5°C (Fig. 2.1b). The high temperature and evaporation with low and unevenly distributed rainfall during the growing season often expose the crops to water deficit causing stress, poor growth and low yields.

2.1.2 Topography and soils

Topographically the plots are located in an area with less than 1% slope falling Northward. As described by van Rensburg (1996) the soil profile characteristics and morphological properties are known as deep freely drained fine sandy loam soil (Table 2.1).

Table 2.1 Important characteristics of the Kenilworth Bainsvlei ecotope Bainsvilei form / Amalia family (after van Rensburg, 1996).

Description	Diagnostic Horizon			
	Orthic A (AP)	Red apedal (B1)	Soft plinthic (B2)	Weathered mud-stone (IIC)
Depth (m)	0.00 – 0.35	0.35 – 1.18	1.18 – 1.40	1.40 – 3.00
Texture class	Fine sand	Fine sandy loam	Fine sandy clay loam	Fine sandy clay loam
Structure	Apedal massive	Rough, weak prismatic	Apedal massive	Rough, strong, jagged blocky
Mottling	None	None	Grey, yellow, red and black	Yellow, black
Colour	Red brown	Red brown	Brown	Yellow orange
Clay (%)	8.5	14	14	24
Bulk density (Mg m^{-3})	1.66	1.68	1.66	1.67
pH (H_2O)	5.2	5.1	6.3	6.5
P (Olsen)	14 mg kg^{-1}			
Ca (NH_4Oac)	561 mg kg^{-1}			
Mg (NH_4Oac)	125 mg kg^{-1}			
K (NH_4Oac)	122 mg kg^{-1}			
Zn (HCl)	2.5 mg kg^{-1}			

The fine sandy loam soils of the experimental site belong to loamy acidic ustorthents. The basic soil morphological properties, according to Soil Classification Working Group (1991), are reddish brown in colour (*Amalia family*) with A-horizon of fine sandy loam texture having particle size distribution of 88% sand, 8.4% clay and 3.6% silt content (Soil Classification Working Group, 1991). The basic concentration of certain plant nutrients are shown in Table 2.1. The soils of the experiment plots are slightly acidic with the pH range of 5.1 – 6.5 down the 3 m profile. The organic matter content in the top layer of the soil is about 0.15 – 0.18% (Woyessa, 2002). The low clay and organic matter content in the topsoil is probably associated with weak surface crust structure that develops on bare soils due to rain drop impact and heat of the sun. Detailed soil profile descriptions for the Bainsvlei area are presented in Appendix 2.1. A summary of the chemical and physical properties of two soil profiles are presented in Appendix 2.2 (The Non-Affiliated Soil Analysis Work Committee, 1990).

2.2 Experimental approach

Field experiments were conducted in two consecutive summer seasons of 2007/08 and 2008/09 at the Kenilworth Experiment Farm on a total area of one hectare. In the first season (2007/08) after the land was prepared for the IRWH technique, the soils was left bare to establish a crust uniformly all over the plot. The area was divided into four replicate blocks (A, B, C & D), with each main plot consisting of four runoff strip length (RSL) treatments (RSL-1 m, 1.5 m, 2 m and 3 m) with rows extending from one edge of the plot to the other in E-W direction (Fig. 2.2).

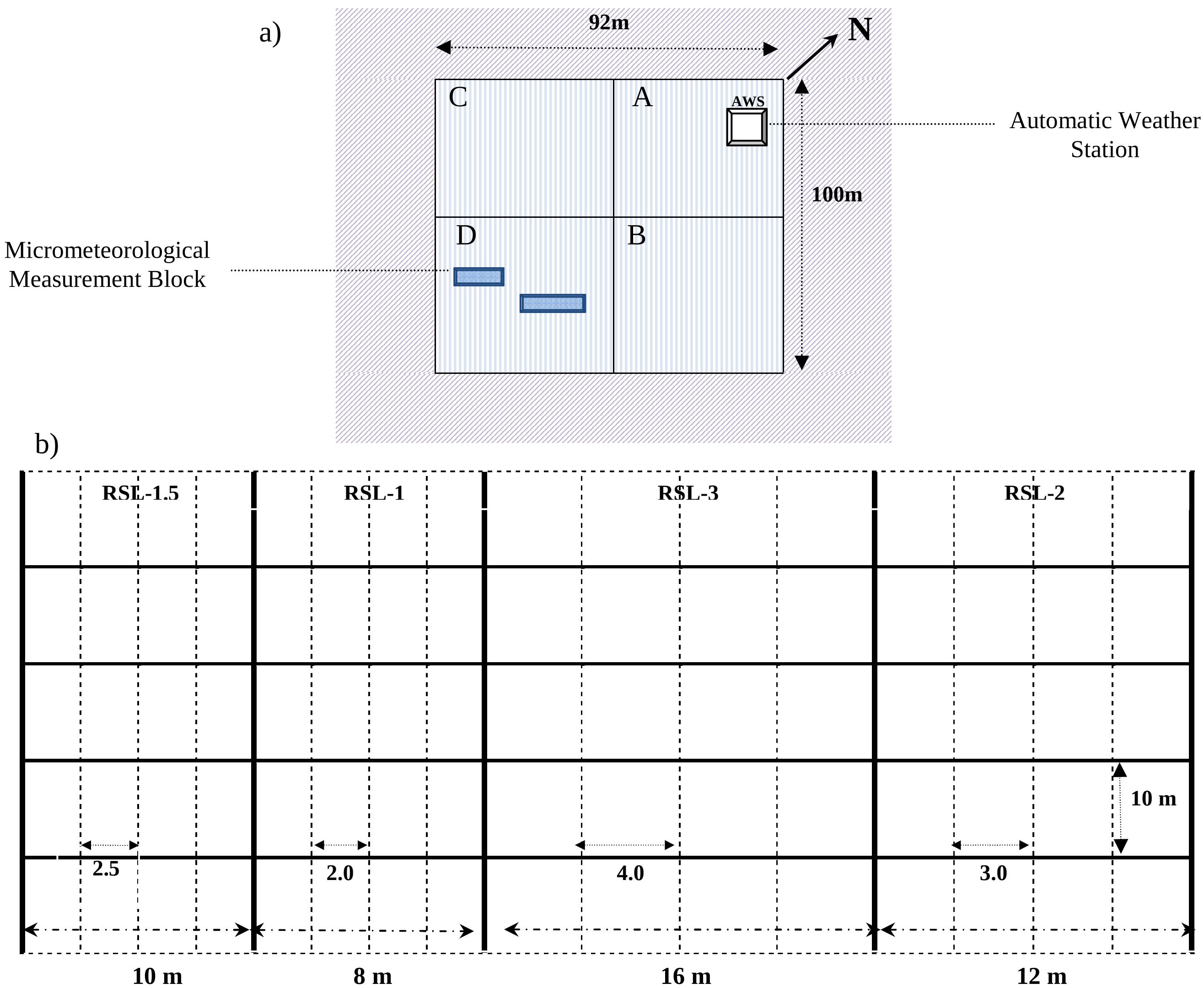


Figure 2.2 Plot layout for IRWH tillage at Kenilworth experimental site: a) Division of blocks (A, B, C and D) with border sides of maize fields (diagonal shaded strips) to meet fetch requirements (not to scale); b) Each block was sub-divided into main plots (RSL treatments) and sub-plots (mulch level).

The five sections from top to bottom (Fig. 2.2b) indicate each sub-plot of the treatment for the different mulch level applications. One block was used for the micrometeorological studies (Block D). The design of the 3×4×5 factorial experiment was conducted as split-split plot randomized complete block design. Each block had four main plots for each runoff size and each of them was further divided into sub-plots of five mulch level applications. Hence, the layout was performed according to four different runoff strip length (RSL) as main plot and five mulch levels as sub-plots. Each sub-plot was 10 m long; and there were four strips per treatments, so that the two strips are effectively the borders (Fig. 2.2b).

2.3 Agronomical practices

2.3.1 Tillage methods

The plots were prepared by using a mouldboard plough and disc in the autumn of 2007 in an E-W direction. Basins with ridges were made against the N-S slope. The runoff strips in the plots were raked with a laser machine on 9 Dec., 2007, to smooth the topsoil, and an even runoff slope was formed in the runoff section by hand on 21 Jan., 2008. Ripping was initially done in the process of land preparation to form a proper basin area, then after a few rain events the crust had formed on the runoff strips by the end of January 2008.

The treatments were arranged according to ratio of basin area to runoff area. The four runoff strip lengths were 1, 1.5, 2 and 3 m and comprised a total plot area that varied between 80 m^2 and 160 m^2 (Table 2.2). The basin area was standardised to 1 m width, resulting in 1.1 m between the plant rows. The main treatment area for each RSL and their ratios of the basin area to runoff area represent the ratio of 1:1, 1:1.5, 1:2 and 1:3. Each plot area was formed with four sets of runoff strip and the adjacent basin area (Fig. 2.2).

Table 2.2 Plot design according to different runoff strip length (RSL) to basin area ratio

Treatments (RSL)	Basin to runoff ratio	Basin area (m^2)	Runoff strip area (m^2)	Treatment plot size × reps. (m^2)	Total plot area (m^2)
1 m	1:1*	10	10	(10+10) × 4**	80
1.5 m	1:1.5	10	15	(10+15) × 4	100
2 m	1:2	10	20	(10+20) × 4	120
3 m	1:3	10	30	(10+30) × 4	160

**Basin area size in all treatments is standardized as width of one meter.*
***On each plot there was 4 sets of basin and runoff sections.*

2.3.2 Mulch application

Mulching studies were done on each runoff length size treatment at five different mulch levels as a sub-plot treatment during 2008/09. The maize stalks of the previous year were used as a mulching material. A mulching level determination was conducted prior to application, by calculating the percentage surface cover using the amount of radiation intercepted through the mulch in a sample quadrant, measured by placing 1m long line quantum (PAR) sensor (LI-COR 191SA) above and beneath the mulch. The range of 0-10 t ha^{-1} mulch surface coverage was used. The percentage of mulch coverage (MC) was calculated using the following formula.

$$MC = \frac{R_{above} - R_{beneath}}{R_{above}} \times 100\% \quad \textbf{2.1}$$

where MC is a mulch level coverage and R_{above} and $R_{beneath}$ are PAR measurements in MJ s^{-1} m^{-2} above mulch cover and underneath the mulch, respectively. Then, the amount of mulch application (t ha^{-1}) was plotted against the mulch cover percentage with the demarcation of below and above 5 t ha^{-1} of mulch cover. Thus, in both cases, there are relationships between percentage of mulch cover and amount of mulch that were fitted to linear function giving a strong coefficient of determination of (R^2) of 0.98 and 86%, respectively (Fig. 2.3).

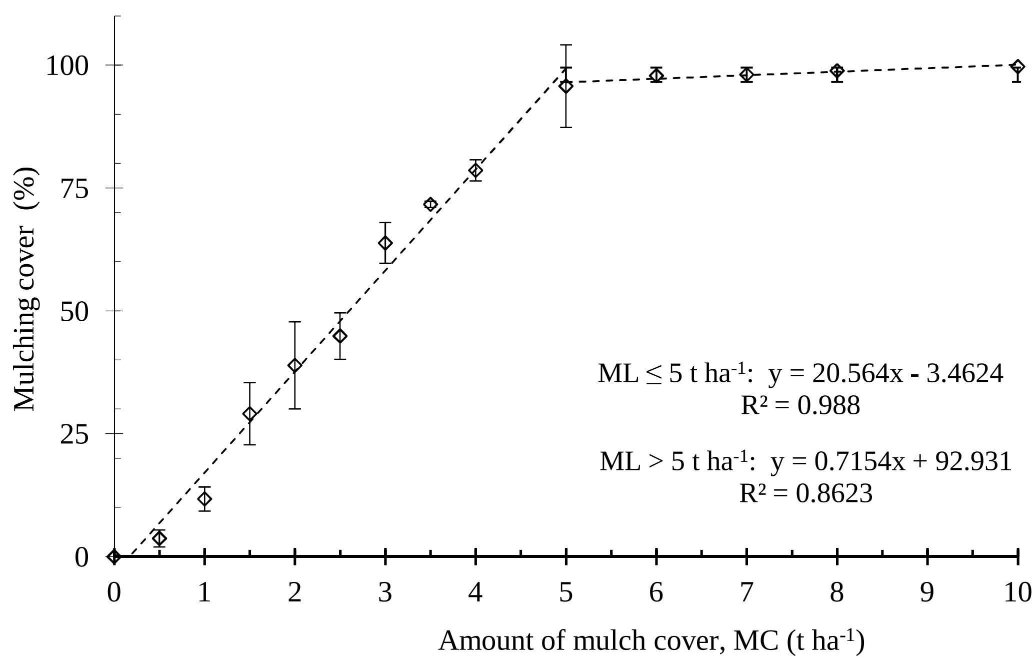


Figure 2.3 Relationship of the mulch amount (t ha^{-1}) and mulching cover (%) from measurements of radiation interception under various amounts of mulch in a quadrant.

From the relationship in Fig 2.3, for the purpose of the field experiment the mulching levels of bare (0), 1, 2, 3, and 5 t ha^{-1} were used to give calculated surface cover of 0%, 12%, 39%, 64% and 96%, respectively. This clearly shows that the highest mulching rate of 5 t ha^{-1} in the experiment represents a maximum surface coverage (near 100%) by the mulch. Fig. 2.4a shows full mulch level cover (ML96%) on runoff strip length of 1.5 m during early growth stage.

2.3.3 Crop management

During the first (2007/08) and second (2008/09) cropping seasons the planting date was on 11 Dec., 2007 and 21 Dec., 2008 respectively. Both seasons (2007/08 and 2008/09) had the maize hybrid, DKC 80-30R (medium maturing variety) but it was planted at a plant density of 24000 in first season and 18000 plants ha^{-1} in the second season, assuming equal plant population per unit plot size. The main reason for higher plant population during the first season was due to the experimental plot remained fallow on the previous year. This implies more water was stored before planting in the profile on the first season compared to the following season. In the first season, planting was done using a planter, whereas in the second season planting was done manually, in order to maintain the runoff structures. Because of the differences in runoff lengths, of the IRWH plots the spacing between plants was adapted to obtain equal plant densities per unit land area. Table 2.3 shows the plant density and spacing (between plants) used on each treatment in 2007/08 and 2008/09 seasons.

Table 2.3 Plant density and spacing between plants in rows of the basin area for different RSL treatments during both growing seasons (2007/08 and 2008/09).

Treatments (RSL)	Basin to runoff ratio	Total plot area (m^2)	Cropping seasons					
			2007/08			2008/09		
			Spacing between plants (m)	Plant #/ plot	Plant #/row/ (10m)	Spacing between plants (m)	Plant #/ plot	Plant #/row/ (10m)
1 m	1:1	80	0.42	192	48	0.56	144	36
1.5 m	1:1.5	100	0.33	242	60	0.44	180	45
2 m	1:2	120	0.28	288	72	0.37	216	54
3 m	1:3	160	0.21	384	96	0.28	288	72

The main reason for decreasing the plant density by 25% (6000 plants) in the second season (2008/09) was due to the fact that there was more stored water in the profile during the first season as 2006/07 was fallow. The experiment was managed intensively to ensure optimal resource utilization and to avoid any stress from weeds or insects or diseases by applying chemicals when necessary. At an early stage, thinning was done to remove excess plants and some side-growth tillers. Fig. 2.4 shows the IRWH plots with the basin and runoff area after dry and wet periods during vegetative growth stage.

Figure 2.4 Maize crop during vegetative growth stage under IRWH system with different cultural management practices during dry and wet periods (2008/09 growing season). (a) showing full mulch cover on the 1.5 runoff section (b) showing water collected in basin area after rainstorm.

2.3.4 Growth stages

For the purpose of this study, the growing period was divided into four phenological growth stages. According to Doorenbos and Kassam (1986), the growth stages for a medium maturity maize crop for grain production are an initial stage of 15 - 30 days, development stage of 30 - 45 days, mid-season stage of 30 - 45 days and late season stage of 10 - 30 days. For this study, the first growth stage (GS-I) comprised 45 days from the planting date on December 21, 2008. At this stage the crop canopy had expanded from the simple germinating seed and leaf appearance processes through to vegetative growth. This stage included the gradual growth of the initial stage into the linear leaf growth phase. In the second growth stage (GS-II), from 46 to 70 days after planting (DAP), the growth increased linearly towards full canopy cover, so overall the total growth period could be expressed as a sigmoidal growth curve. In the later growth stages (GS-III and GS-IV) after reaching maximum canopy, crop tasseling starts and proceed to grain filling and then maturity phase, these growth stages were 71 - 105 DAP and 106 - 150 DAP, respectively.

2.4 Field measurements

2.4.1 Weather variables

An automatic weather station (AWS) had been installed at standard height of 1.5 m by ARC-ISCW (Agricultural Research Council of South Africa - Institute of Soil, Climate and Water) from Pretoria. The AWS consists of tipping bucket rain gauge, cup anemometer and wind vane; a pyrometer and combined temperature and humidity sensor. All meteorological data (rainfall, minimum and maximum temperatures, minimum and maximum relative humidity, wind speed and direction, and solar radiation) were recorded on a CR10X data logger (Campbell Scientific, USA) every 5 minutes and averaged over one hour for storage. The rainfall recorded from the AWS during the season was obtained on a 5 minute rainfall amount basis. Thereby each rain event can constitute several rainstorms and various rainfall durations were considered for each runoff measurement (see Chapter 3).

2.4.1.1 Rainfall during growing seasons

During the two growing seasons (Dec. - May) precipitation was 282.5 mm and 249.8 mm, respectively (Fig. 2.5). Both seasons received less than the long-term mean (350.2 mm) during the growing season.

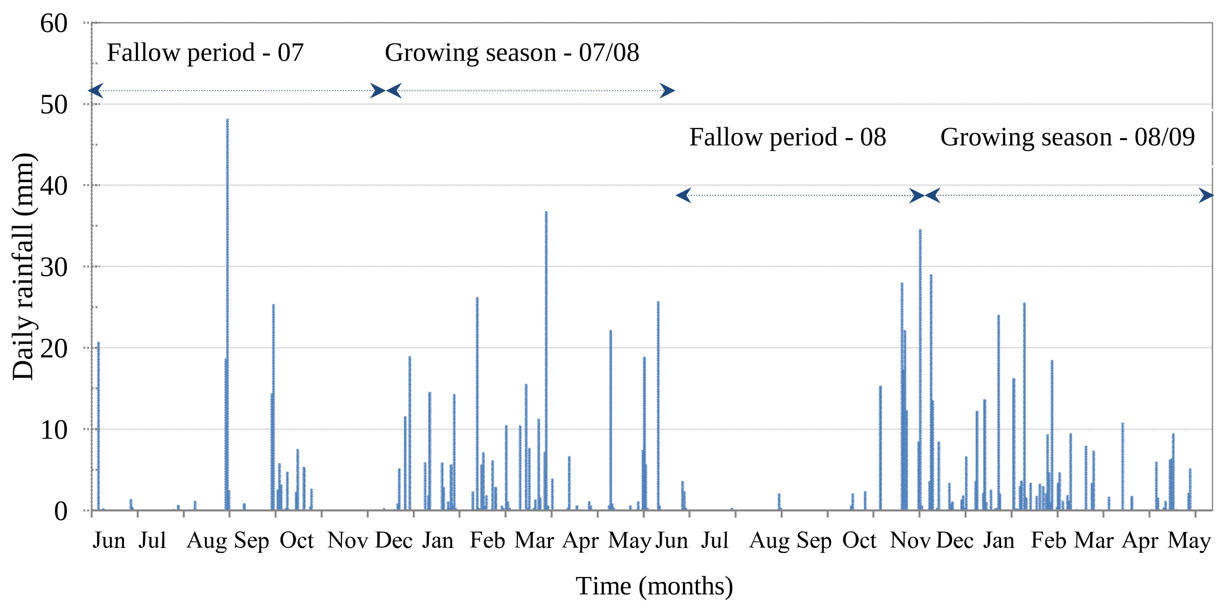


Figure 2.5 Daily rainfall distributions for both first (2007/08) and second (2008/09) growing season with a fallow period between the two seasons.

Rainfall was erratic in nature and 35% of the amount of rainfall was concentrated in February - March for the first cropping season and in Jan. – Feb. for the second season. During February, the crop received 65 mm rain in the first season and 68 mm in the second season, being 23.5% and 25% of the total rainfall, respectively. While during the planting time in December, the precipitation was low in the first cropping season, and during the second cropping season the rain was mainly concentrated at the beginning and end of that month. However, pre-planting was almost the same in both seasons from August to November 215.1 and 191.2 mm of rain was received in 2007 and 2008, respectively.

2.4.1.2 Reference evapotranspiration during growing seasons

The trend of reference evaporation (ETo) for each growing season shows maximum daily ETo occurred in the first 20 days during the 2007/08 season and between 40 and 50 days after planting in 2008/09 season (Fig. 2.6). The maximum ETo was approximately 10 mm d^{-1} and 9 mm d^{-1} for the first and second growing seasons, respectively. The results clearly show the natural decreasing trend of ETo over the growing season. In the first growing season the ETo was slightly higher (about 8 mm d^{-1}) in December compared to the second growing season (6.5 mm d^{-1}).

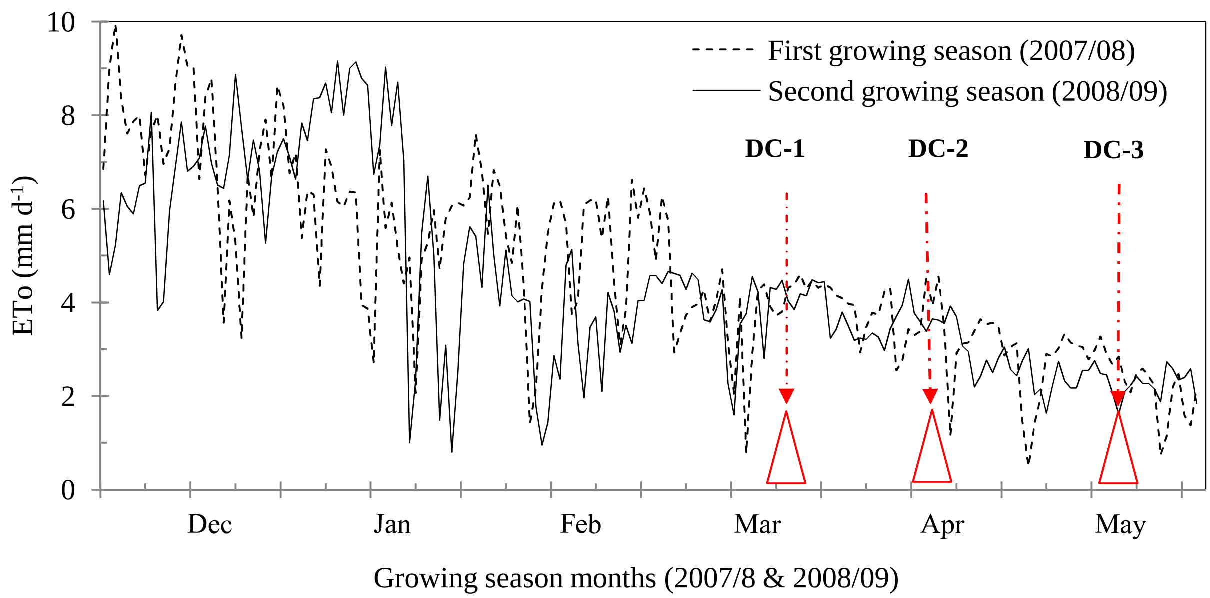


Figure 2.6 Daily reference evapotranspiration (ETo) over the growing period of 2007/08 and 2008/09. The arrows indicate the three drying cycles (DC) for the soil water evaporation measurements during 2008/09.

During second growth stage from 70 - 90 days the ETo was 6 mm d^{-1} during the first season and about 2 mm d^{-1} less during the second growing season. However, both seasons had similar ETo values of about 4 mm d^{-1} in the period of mid-Mar. to mid-Apr. It appears that the variation of ETo was controlled by the variation in the climatic factors particularly in the natural progression of seasonal temperature and rainfall. ETo generally decreased with days after planting, so that the measured Es should be affected by the declining atmospheric demand during different drying cycles.

2.4.2 Soil water parameters

2.4.2.1 Soil water content

To monitor the soil water content of the root zone θ_r, neutron water meter steel access tubes were inserted to a depth of 1.8 m, that is, to a depth greater than the expected roots. During the cropping season 2007/08 and during the fallow period in 2008 access tubes were installed in the center of the basin area and in the runoff section of each plot. Whereas, in cropping season 2008/09 (second growing season) additional tubes were installed at each one meter interval across the runoff section. Soil water content was measured at an interval of 1-2 weeks to a depth of 1.8 m using a neutron water meter or neutron probe (NWM) (Campbell Pacific Nuclear model 503, CA USA, 1994) to take neutron counts down the access tubes (37.5 mm internal diameter). Measurements of θ_r were carried out before and at planting periods and during the growing season at 300 mm depth intervals starting at 150 mm (being 150, 450, 750, 1050, 1350, 1650 mm). This procedure ensures that the different pedological layers in the soil have been adequately represented. More detailed pedological layers characteristics of the soils at the experimental site (Bainsvlei form / Amalia family soil type) are attached in Appendix 2.1.

The neutron probe was calibrated for the site in a separate study done by Chimungu (2009) for this particular experimental farm. It was calibrated for every soil layer by using gravimetric soil water measurements (θ_m) and bulk densities of the soil (Robinson and Hubbard, 1990). A range of NWM counts for every soil layer, under wet and dry conditions, was made, with samples for gravimetric θ_m determination taken at the same time close to NWM access tubes. The θ_m values for every soil layer were multiplied by the appropriate bulk density value to give volumetric soil water content (θ'_v) of that soil layer. The linear relationship between NWM counts and θ'_v values provided the calibration equation.

2.4.2.2 In-field runoff

The runoff measurements were carried out only during the second cropping season of 2008/09 on the bare, 39% and 96% mulch treatments of each runoff to basin area ratio size plot during each of 12 rainstorm events. Depending on the rainfall pattern, the runoff was measured the day after the rainstorm event occurred, whereby runoff was accumulated over the whole rain event, which can constitute several rainstorms with various rainfall durations. The runoff measurement plots (Fig. 2.7) were prepared within the corresponding treatments by constructing enclosure frames. The galvanized iron sheeting (30 cm wide) was installed (restrained by pegs to stand upright) on three sides, across the runoff strip and near the next row of plants. The iron sheets were inserted into the soil surface to 5 cm depth to ensure that runoff was measured only from within the enclosure metallic frame area. A gutter was connected at the outside edge of the basin area to transfer the runoff water into a 200 litre collecting drum (Fig. 2.8).

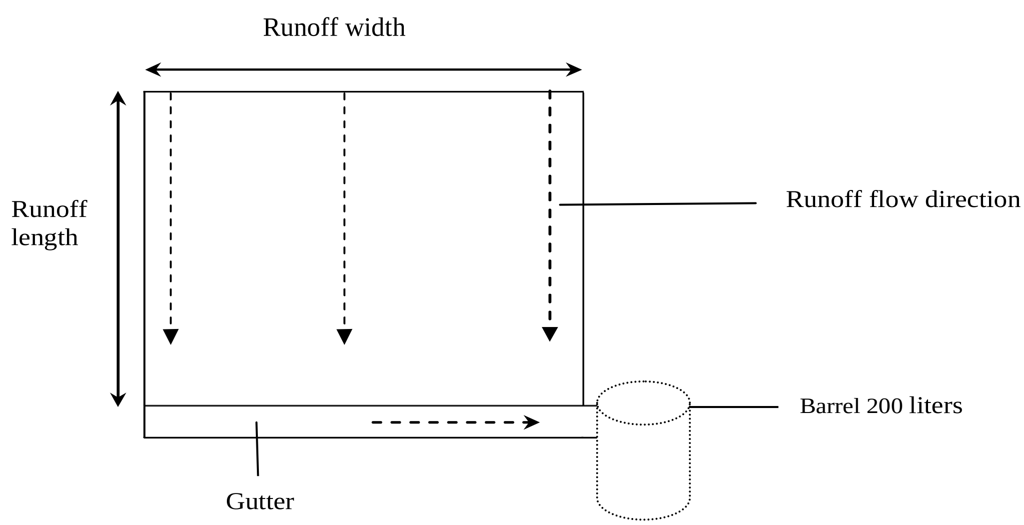


Figure 2.7 Schematic layout of the runoff plots used in the experiment. The frames were fitted along the width of the runoff area.

After every storm event the runoff collected was discharged from the drum by using a small mobile pump devise to measure the volume manually using a graduated bucket and again weighed using a digital scale in the field.

Figure 2.8 Runoff plot measurement frames for bare and mulched treatments, 2008/09. Arrows indicate the direction of runoff towards basin area.

2.4.2.3 Soil evaporation

Evaporation of water from the soil surface beneath the maize crop canopy was measured using microlysimeters containing undisturbed soil samples during three consecutive drying cycles (as indicated in Fig. 2.6) each after a rain event.. The periods selected for soil evaporation measurement were after the crop had reached its maximum canopy cover during the second season of the experiment (2008/09).

Microlysimeters (MLy) were constructed according to Boast and Robertson (1982) and Hoffman (1997), with an inner pipe made of steel tubing of 71 mm diameter and 300 mm deep and sealed with a stopper at the bottom end. The outer liner was a PVC pipe with diameter 80 mm. To preserve the heat conduction processes between the two pipes a strip of cloth was taped at the top part of the liner pipe to stop air movement. A total of 33 individual microlysimeters were used for selected treatments (bare, 39% and 96% mulch cover), being installed according to runoff strip length. The microlysimeters were situated at the centre of basin area and in each one meter interval of the runoff length, in order to differentiate between the effect of canopy shading by the maize plants.

The MLy undisturbed core samples were taken after a rainstorm within the same plot by drilling the core sampler into the surface at the allocated plot position, in order to place the soil layers in the right direction without compaction. The bottom end was then covered with a sealed stopper to prevent drainage and/or soil loss. After the hole was created by the extraction of the soil core for the microlysimeter, it was widened using a 65 mm diameter auger and the PVC pipe was inserted into the hole to line the cavity. The outer liner served as a sleeve to allow the microlysimeter to be reinserted after weighing.

The microlysimeters were weighed daily with a precision of 0.01 g and returned to their respective sleeves (PVC pipes) in the ground in their plot of origin so that their surfaces were at the same level as the surrounding soil. All measurements were performed between 08:00 – 09:00 local time for 7 days in succession. Thus, they were reweighted after each 24 h time period to determine the water loss. The differences between the two masses divided by the circular cross-sectional area of the inner pipe (cylinder) is the cumulative soil evaporation flux during that time period (g m^{-2} d^{-1}). When collecting and returning the MLy to the field, care was taken to ensure that the site around the MLy was disturbed as little as possible in an attempt to ensure integrity of the soil surface and canopy around the MLy. For the mulched treatments, extreme care was also taken to make sure that the MLy was recovered by the appropriate mulching rate for the corresponding treatments.

2.4.3 Micrometeorological parameters

During the maize cropping season, as part of continuous micrometeorological measurements, profiles of temperature, humidity, wind speed and other standard energy balance parameters were measured for micrometeorological studies (Fig. 2.9). Data from the automatic weather station were used to calculate reference evaporation (ETo) using the FAO-56 Penman-Monteith method (Allen *et al*., 1998).

2.4.3.1 Profile of meteorological variables

Within canopy profile measurement

During these measurements, three consecutive growth stages with specific runs were selected. The growth stages represent vegetative growth stages when the crop canopy had attained 1.2 m and 1.6 m height, and during the final stage with an average canopy height of 2.2 m. The profile measurements within canopy were performed at the heights of 0.30, 0.60, 0.90 &1.20 m; 0.40, 0.80, 1.20 & 1.60 m; and 0.55, 1.10, 1.65 and 2.20 m for the period of DOY 36 - 42 (5-11 Feb.), DOY 51 - 56 (20-25 Feb.) and DOY 69 - 74 (10-15Mar.), respectively. The sensors for measuring air temperature, humidity and wind speed were moved periodically within the crop canopy between wide and narrow runoff strips simultaneously. The field layout and measurement positioning are marked in sketch diagram in Fig. 2.2.

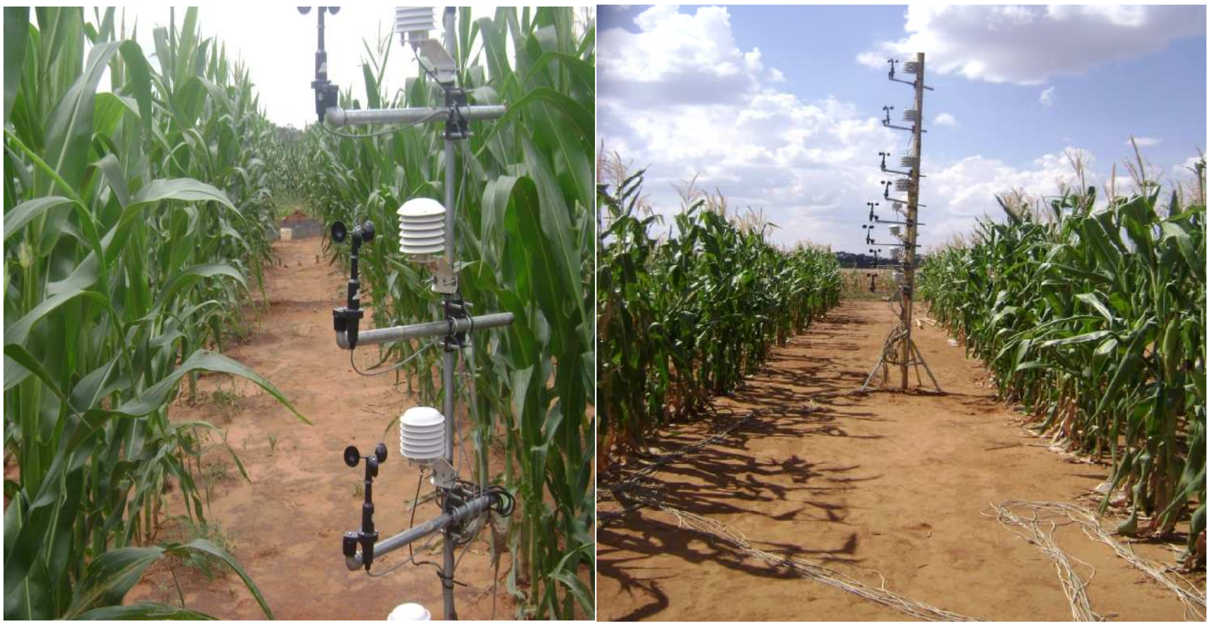


Figure 2.9 Sensor arrangements in the runoff section of maize canopy at 1.6 m crop height on 25 Feb., 2009 for 1.5 m length runoff strip and within and above the maize canopy up to reference height of 4.5 m on 07 May, 2009.

Within and above canopy profile measurement

As part of the measurement plan, profiles of heat, mass and momentum were undertaken within canopy and from the top canopy layer up to a reference level of 4.5 m. The instrument set-up used similar procedures, except the location of the sensors was different for different measurement purposes. A long mast was buried deeply and attached to a tripod stand in order to hold the sensor arms firmly at the needed height. For the above canopy measurements, sensors collected observations every 5 minutes and averaged hourly temperature, humidity and wind speed at heights of 1.8, 2.1, 2.4, 2.7, 3.0, 3.3 3.9 and 4.5 m from ground surface (Fig. 2.9). Precipitation measurements were obtained from AWS inside the experimental plot in order to differentiate dry and wet conditions during micrometeorological measurement period. The observations were taken in wide and narrow runoff strips in 2008/09 cropping season during DOY

107-121 and DOY 122-132 respectively, as insufficient instruments were available for simultaneous measurements.

2.4.3.2 Net radiation and soil heat flux

The *Rn* was measured at a height of 1.5 m in the centre of the wide runoff strip with nearby plants cleared to represent the bare soil surface, and is regarded as positive for incoming energy. Due to this placement of the Rn sensor, it may be receiving some reflected radiation from the surrounding crop rows. Therefore the Rn will be calculated from models to be discussed later in Chapter 10. The four soil heat flux plates of CN3 type were installed at 0.08 m soil depth by excavating a shallow trench, creating small slits in one sidewall just smaller than the plate dimensions then inserting the plate into the slit and back filling the trench.

2.4.3.3 Instrumentation

The following instrumentation were used for micrometeorological studies:

- Automatic weather station consists of a tipping bucket rain gauge, cup anemometer and wind vane; a pyrometer and combined temperature and humidity sensor.
- Wind speed was measured using three-cup wheel Sentry anemometers (Model 03001) with stalling speed of about 0.15 m s^{-1}.
- Temperature and humidity were monitored using HMP50 temperature and relative humidity probes (Campbell Scientific, USA), which contains PRT and Vaisala-INTERCAP sensors. The HMP50 sensors were housed inside white plate radiation shields (41303-5A Model).
- The net radiation was measured with a NR-LITE-L Net Radiometer at a height of 1.5 m in the centre of a wide runoff strip.
- The four flux plates used for soil heat flux measurements were CN3 type (Carter-Scott Manufacturing Pty. Ltd., Brunswick) and installed at 0.08 m soil depth.
- Hourly soil temperatures were measured using thermocouples (0.511 mm copper/constantan) at depth of 0.02 and 0.06 m.
- The mass based soil water content was measured at depth of (0.08 m) using two ECH_2O Probe sensors.

All micrometeorological data were recorded on a CR1000X data logger (Campbell Scientific, USA), every 5 minutes and averaged over one hour for storage. Instrumentation was frequently checked and data regularly downloaded with some overlap from the previous download. Periods for which the measured entity was outside the limits of the range, were then rejected.

2.4.4 Crop parameters

Leaf area and biomass samples were taken for each plot from rows on both the ridge and basin side. Plant densities were assessed after emergence and plant counts were done after full cover on a 10 m length of row in each plot. Crop growth stage was recorded regularly and visual symptoms were used to identify the critical growth stages (Turner, 1986; Laker *et al.,* 1991).

2.4.4.1 Leaf area and plant height

Leaf area (LA) was measured using the leaf area meter (Model LI3100, LI-Cor Inc., Lincoln NE). Leaf area index (LAI) is the ratio of the area of green leaf surface produced by crop plants to that of cropped area. However, in this study, the LA were expressed over the basin area ratio or the land area between the maize row (1.1 m) and denoted by “BLAR”. This meant that the LA was calculated from the same unit area for all RSL treatments with varying plant densities. This helps to effectively categorize the shading pattern of the treatments.

During the second season (2008/09) leaf area was measured at intervals of ten days from day 25 DAP to 65 DAP. As the leaf area for the first season (2007/08) had only been measured once at tasseling stage, a seasonal BLAR trend was estimated using an interpolation of leaf area measured during the second season from different runoff strip treatments. Since different runoff strip length treatments comprise different plant densities per unit area and the two seasons had different plant population (i.e., 24000 for the first season and 18000 for the second season). This implies that, the plant densities were 4.4, 5.5, 6.5 and 8.5 plants $m^{-1}$for the first season and 3.3, 4.1, 4.9 and 6.4 plants m^{-1} for the second season.

2.4.4.2 Dry matter production

The same plants as those measured for leaf area were used for dry matter accumulation measurements. Thus, the dry matter was measured periodically from 25 days after planting until the plant attained maximum size (65 - 70 days after planting). During sampling, the height of each plant was recorded and then cut at the soil surface and then separated into green and dead leaves, stems and reproductive organs. At the beginning of the season, three above ground plant samples were harvested from each replication but in later growth stages only two plants were taken from each basin and ridge side to determine the harvested biomass. Samples were dried in an oven regulated at 70^oC for 72 hours. Thus the biomass partitioned into leaf, stem and reproductive organ were calculated as oven dry material, and converted to the unit of kg ha^{-1}.

2.4.4.3 Grain yield

Grain yield of maize crop was determined from final quadrant samples by harvesting 4 m length of row along each basin and ridge side at the end of the season from each replication. The grain was shelled and weighed after oven drying and adjusted to 12.5% seed moisture content and expressed as kg ha^{-1}.

2.5 Statistical analysis

Analysis of variance was done for the comparison of the different treatments using different statistical software packages: such as SAS 9.1.3 for Windows (SAS Inst Inc., 2006), SPSS computer programme for Windows (SPSS Inc., 2008) and Graphpad Prism 5 (Graphpad Software, 2007). Means were compared using the LSD test. Significance levels of $P \leq 0.05$, 0.001 and $P \leq 0.0001$ were used, based on the variability associated with the type of measurements. Empirical relationships of the parameters were derived using regression procedures. Measured and estimated values were compared using regression procedures and mean statistics given by Willmott (1981; 1982) were calculated. For various experiments in the study, different statistical designs were adopted according to the nature and magnitude of the trail. Thus, for each trail a detailed statistical analysis method is presented in each specific chapter.

CHAPTER 3

Effect of Runoff Strip Length and Mulch Cover on In-field Runoff

3.1 Introduction

In the tillage technique of in-field rainwater harvesting (IRWH), rainfall-runoff processes are modified in a major way by the cultural management practices. Relating runoff to rainfall amount is an approach widely used in many semi-arid climates, where water resources are usually the most limiting factor. Under practical crop production conditions, the theoretical relationship of rainfall amount, intensity and duration to runoff has great importance and is fundamental to the success of the IRWH technique. Due to this fact, for the last few decades much attention has been given to studying the rainfall-runoff processes and relationships, especially under dryland crop production (Boers and Ben-Asher, 1982; Hensley *et al.,* 2000; Walker and Tsubo 2003a; Botha *et al.,* 2003; Bothma, 2010; van Rensburg, 2010; Ibraimo, 2011; Mzezewa and van Rensburg, 2011).

Estimating in-field runoff is also particularly difficult, due to many options for management practices such as different tillage techniques and various types of mulching. Application of different cultural practices on the runoff strips influences the amount of rainwater harvested. It is also expected that it will vary through a growing season. Different studies showed that the amount of rainwater harvested was affected by mulch cover, crop residue and vegetative cover, initial soil roughness and aggregate tension of the soil (Morin and Cluff, 1980; Fohrer *et al.,* 1999; Cerdan *et al.,* 2001; Ruan *et al.,* 2001; Le Bissonnais *et al.,* 2005; Bothma, 2010). Therefore, to recommend appropriate techniques on the runoff area when practicing IRWH, a theoretical and practical understanding of the relationships between rainfall and runoff is of paramount importance.

Many studies in South Africa have revealed the importance of rainfall-runoff relationships in crop production: Haylett (1960), du Plessis and Mostert (1965), Bennie *et al.* (1998), Hensley *et al.* (2000). In other recent studies Walker and Tsubo (2003a & b), Botha *et al*. (2003), Zere *et al.* (2005), Anderson *et al.* (2007), Welderufael (2007) and Joseph *et al.* (2011) focused on the relationship between rainfall and runoff. The results of long-term rainfall-runoff experiments are particularly valuable. Bennie *et al*. (1998), after many years of research, emphasized that much more research is needed to estimate runoff reliably due to the complex nature of the actual runoff since it is influenced by several factors including rainfall intensity, slope of the land, initial and final infiltration rates, initial soil water content and roughness of the surface. Therefore, the practical measurement of in-field runoff will be advantageous in evaluating the relationships of the amount of runoff water harvested from those particular rainstorms that produced runoff.

Hensley *et al.* (2000) mentioned that the adoption of a linear regression analysis, using rainfall as independent and runoff as dependent variable yield a reasonable relationship. Worku and Hailu (1998) also successfully applied a multiple regression analysis to quantify runoff and soil loss from different tillage methods coupled with alternative cropping systems in the Central Highland vertisols of Ethiopia. Furthermore, with the availability of rainfall intensity data, Hensley *et al.* (2000) suggested the possibility of developing runoff models to simulate runoff during rainstorm events.

The rainfall-runoff process is well described in the literature. Numerous papers on the subject have been published and many computer simulation models have been developed. In particular the effect of mulch for dryland crop production on the tillage system was studied in great detail (Lal 1998; Woyessa and Bennie 2004) and on runoff strips in IRWH (Hensley *et al.,* 2000; Botha *et al.,* 2001; van Rensburg *et al.,* 2002; Anderson, 2007). For instance, the difficulties in accurately measuring and predicting the effect of different mulches placed on the runoff strip were researched on two different soils at Glen, Bloemfontein (Botha, 2006). In addition runoff amount and sedimentation in the runoff water resulting from bare, stone and organic mulch on a 2 m runoff strip was also measured on those different soils. In that study, organic mulch clearly suppressed runoff on an average of seven to ten times less than from the bare plots thus enhancing infiltration in the runoff area. But the remaining concern is: ‘Which combination of mulching level and runoff strip length can be the most beneficial in terms of precipitation use efficiency in semi-arid areas?’ As in the case of this study on fine sandy loam soils.

None of the research studies mentioned have answered the basic question of how the amount of water harvested is influenced by runoff strip length in combination with mulch coverage of the runoff strips. Therefore the goal of this study is to improve the understanding of rainwater harvesting under different surface conditions i.e. runoff strip lengths and mulch cover. The specific aims are:

- to quantify the effect of surface properties (various runoff strip lengths and mulch levels on the runoff part) in the IRWH tillage technique during the maize growing season on the Bainsvlei Kenilworth ecotope, and
- to derive a simple empirical model to predict in-field runoff based on rainfall event characteristics and cultural practices under the IRWH system.

3.2 Materials and methods

3.2.1 Treatments

The main experimental design and treatments were described in Chapter 2, Section 2.2. Accordingly, there were four runoff strip lengths (RSL) and five mulch surface cover levels (hereafter called mulch levels, ML) each combination treatment replicated three times. The RSL treatments were comprised of 1, 1.5, 2 and 3 m runoff lengths and the ML were 0% (bare), 12%, 39%, 64% and 96%. For this part of the study, all the RSL treatments and three of the ML treatments, viz. 0, 39% and 96% were used.

3.2.2 Rainfall characteristics analysis

During the growing period, rainfall intensity (at 5 min intervals) was recorded by the automatic weather station (AWS) at the experimental site. For this measured field runoff data analysis during the growing season of 2008/09, the rainfall pattern was characterised through the growing season, in terms of amount, duration, peak intensity, mean and median intensity, using a 5 minute time interval data for this analysis (Appendix 3.1).

In this study, a ‘rainfall event’ was considered as a rainstorm, as a group of rain segments even if separated by more than three hours. This is in contrast to Walker *et al.* (2005) who defined a ‘rainfall event’ as continuous precipitation, with dry intervals of a less than a specific length of time, which was usually 3 hours. For this study that definition, could give more than one rainfall event in a 24 hours period according to the rainfall record. However, the runoff measurement were only done every 24h after the end of the rainfall event, so here a number of rainstorms can constitute each rainfall event from which runoff was produced, regardless of duration or intermittent dry period. An analysis of rainfall characteristics was done for the long-term record (15 years) extracted from 1-minute resolution dataset of the rainfall events at Glen (Glen Agricultural College; 28°56'S, 26°20'E, 1304 m) (ARC-ISCW Climate Data Bank). The rationale of this analysis is firstly, the assumption that the sites are near enough to each other and they are both influenced by the same convective rainfall systems. Secondly, that the Glen 15 year record (1992 – 2007) measurements only available since use of an automatic weather station, can give a representative statistical characterisation of the long-term rainfall, within this general region, in terms of amount, duration and intensity. Therefore the comparison with observed rainfall events during the specific growing season at Kenilworth is valid.

3.2.3 In-field runoff measurement

The method of runoff collection was described in Chapter 2, Section 2.4.2.2. These runoff measurements were performed during the 2008/09 growing season over 12 runoff events. The measurements were done after the rain days, therefore several rain storms were considered in each event and the resulting runoff measurement. The approach of dividing the cropping season into growth stages (Chapter 2, Section 2.3.4) for the runoff measurements was used to explain the runoff processes in relation to plant canopy development.

The volume of collected water (in-field runoff) after each rainfall event was obtained from the mass of runoff water collected in the drum. The volume of runoff water recorded was recalculated as runoff per unit land area (1 m^2). The volume (m^3) was divided by the net area of runoff collection plot to obtain the runoff in mm to match the units used for rainfall. To obtain the net area of the runoff plot, the area occupied by the gutter was subtracted from the total area of runoff plot measurement enclosure (Chapter 2, Fig 2.7). This approach used the logic that 1000 kg = 1000 litre = 1 m^3. Therefore the calculated amount of runoff in volume over the net runoff plot area can yield the amount of runoff (in mm i.e. as a rainfall equivalent) harvested by the basin area.

Some of the runoff events at the beginning of the season, during crop establishment were not measured as the measuring metallic frame was only put on in place 23 days after planting (DAP). Unfortunately, two runoff measurements from a bare 3 m runoff strip length plot were not recorded due to broken structures after violent storms. The amount of sediment collected from the runoff strip was minimal and considered as insignificant in this study. However, it can be stated that the 12 sequential practical field measurements of runoff from both bare and mulched (39% and 96% mulch cover) treatments for each RSL can represent the growing season.

3.2.4 Statistical analysis

Due to the magnitude of the experiment, only one replicate was employed. In this case the application of a two factor split plot arrangement is suited to carry out such an experiment (Sokal and Rohlf, 1981; Box and Jones, 1992). Two way interaction effect of RSL × ML treatment analysis was adopted using the statistical software SAS 9.1.3 for Windows (SAS Institute inc., 2006). Means were compared using the LSD test. Significance levels of $P \leq 0.05$, $P \leq 0.001$ and $P \leq 0.0001$ were used, based on the variability associated with the type of measurements. In-field observed dataset from different treatments were combined and divided equally into two, with random selection, for deriving and verifying purposes of the model. To statistically test the differences in runoff amount between the treatments, a multiple regression analysis was applied by using the SPSS computer programme (SPSS Inc., 2008). In-field runoff was simulated using stepwise regression models with rainfall amount, peak rainfall intensity and runoff strip length and mulch level as agronomic practices. Willmott method (1981; 1982) was used to compare the simulated and measured values statistically. The ability of the model to predict Ro was also evaluated using the long-term rainfall event data points from Glen.

3.3 Results and discussion

3.3.1 Rainfall characteristics

Rainfall was characterized with respect to event amount, duration and peak intensity (Table 3.1). The crop received a total amount of 249.8 mm from 57 rainstorms during the 2008/09 growing season. The mean duration of rainstorms amounted to 135 minutes with a mean peak intensity of 9.8 mm h^{-1}. Compared to the long-term mean statistics over same months; the mean number of rainstorms per season is 76, the mean rain event duration is 130 minutes and peak intensity is 22.5 mm h^{-1}. In order to obtain a better understanding of how the rainfall characteristics compare with the long-term statistics, data was divided into classes. The comparison reveals the following: firstly, the lowest amount category (<1 mm) for growing season gave 23% of all identified events, which is higher than the long-term records (3%), however this information lacks confidence because of the consideration of all single-tip events (0.1 mm). For instance, Dunkerley (2008) and Zerizghy *et al.* (2012) found comparable single-tip events of about 23% and 19.5% of all long-term identified events and suggested this is due a characteristic of the tipping bucket measurement technique that does not provide an indication at what time the rain starts, but only a time when the first 0.1 mm is received. For the same site (Glen) in the statistical analysis study, Walker and Tsubo (2003a) excluded the data of single-tip per rainfall event because of no specific measurement of the starting time of each rainfall event.

Table 3.1 Class range of rainfall event amount, duration and intensity with corresponding percentage for Glen Agricultural Institute historical dataset (15 years) from ARC-ISCW as analysed by Zerizghy *et al.* (2011) and for 12 observations (Obs.) made during this project 2008/09 growing season at Kenilworth Experimental Farm.

Event amount			Event duration			Event peak intensity		
Class range (mm)	Percentage of representation		Class range (min)	Percentage of representation		Class range (mm h^{-1})	Percentage of representation	
	Obs.**	Long-term*		Obs.**	Long-term*		Obs.**	Long-term*
x ≤ 1	23.1	3.1	x ≤ 1	-	1.1	x ≤ 10	71.2	4.4
1 < x ≤ 8	61.5	29.9	1 < x ≤ 30	21.2	6.2	10 < x ≤ 25	15.4	28.9
8 < x ≤ 15	11.5	25	30 < x ≤ 60	23.1	7.4	25 < x ≤ 50	13.5	32.8
15 < x ≤ 20	1.9	10.5	60 < x ≤ 90	3.8	6.6	50 < x ≤ 75	-	16.7
20 < x ≤ 25	-	6.6	90 < x ≤ 120	5.8	7.0	75 < x ≤ 100	-	12.2
25 < x ≤ 30	1.9	2.8	120 < x ≤ 150	15.4	6.5	x > 100	-	5.0
30 < x ≤ 40	-	10.6	150 < x ≤ 180	11.5	3.9			
40 < x ≤ 50	-	3.8	180 < x ≤ 240	7.7	10.6			
x > 50	-	7.7	240 < x ≤ 300	3.8	9.2			
			300 < x ≤ 360	1.9	4.7			
			360 < x ≤ 480	3.8	7.9			
			480 < x ≤ 600	-	9.2			
			x > 600	1.9	19.5			

**Long-term rainfall dataset for Glen as analysed by Zerizghy et al. (2012)*
*** Obs. = Observed 2008/09 growing season dataset for Kenilworth site.*

Secondly, the growing season received far more rainfall events of low amounts (between 1 mm and 8 mm) compared to the long-term; 62% compared to 30% in the long-term dataset. This also explains why there were a high percentage of rain events of short duration (< 60 minutes) and low intensity (≤ 10 mm h^{-1}) compared to the long-term. This type of rainfall event would normally be discarded in runoff estimation, because they do not produce a significant amount of runoff. This might be true for conventional tillage where the soil surface is rough, but under IRWH with a smooth, crusted surface the situation might change. For instance, in a study quantifying rainfall-runoff relationships (Welderufael *et al.*, 2008), a threshold value of rain event amount of 9 mm with peak intensity of > 6 mm h^{-1} were chosen to yield the best performance model for runoff estimation. However, the considerations of only relatively large and intense rain events for in-field runoff estimation failed to provide reliable runoff estimation.

Thirdly, the rainfall events that fell during this season in the moderate amount class (from 8 to 20 mm) were poorly scattered compared to the long-term. However, in the observed dataset there are a total of 28 events (represents 54% of total number of events) with duration between 1 and 120 minutes, and with peak intensities (45 rain events) in the classes less than 25 mm h^{-1}. These types of events will be invaluable for analysing in-field runoff. There was also a distinct lack of high (30 - 50 mm) and very high (> 50 mm) rainfall events during this growing season. In addition, during 08/09 growing season, peak intensity greater than 50 mm h^{-1} never occurred, while over the long-term there were a considerable number of events between 50 and 100 mm h^{-1} and even greater than 100 mm h^{-1}, with 29 and 5%, respectively. Therefore, it is not always useful to refer to long-term rainfall event characterization for a particular growing season, especially for the extreme lowest and highest classes.

3.3.2 Effect of surface treatments (RSL & ML) on runoff

The information in Table 3.2 reflects the rainfall characteristics, of each rainfall event and the resulting runoff (Ro) as influenced by the surface treatments (RSL and ML) within different growth stages (GS). GS-I represents the period from day of planting to 45 DAP and GS-II, GS-III and GS-IV represent 46 – 70, 71 – 105 and 105 – 150 DAP.

A total of 12 runoff-producing-rain events were measured, four events in GS-I, three events in each of GS-II and III and two events in GS-IV (Table 3.2). The rainfall event amounts were in the range of 6.5 to 25.9 mm, with peak intensities varying from 4.8 to 46.8 mm h^{-1} (Table 3.2). The duration of the rain events included long intermittent rainfall for about a day and short storms of one hour. As is typical of this region, rain events are highly variable in terms of amounts, intensities and durations. There was a reasonable linear relationship (R^2= 0.61) between rain event amount and duration, but no linear correlation was found with peak intensities. This is probably due to the small size of dataset available for rains that produced runoff during this growing season. Walker and Tsubo (2003a) analysed relationships of long-term peak rainfall intensity with rainfall event amount and duration for three semi-arid areas in this region namely Glen, Bloemfontein and Pretoria. For all areas, they found little or slightly better correlation between rain event amount and intensity, with R^2 value varying from 0.20 for events of long duration to 0.70 for events of short duration. As a result the collectable runoff during the growing period is largely dependent, not only on the amount of rain but also on the intensity and duration, which could be the reason for variable crop production. Furthermore, the in-field runoff amounts produced were also affected by the surface treatments, such as length of runoff strip and mulch level across the growth stages.

Table 3.2 Characteristics of rainfall events, when measurable in-field runoff occurred and runoff amount Ro (mm) measured from different mulch (ML) and runoff length (RSL) treatments during the growing season 2008/09 (see text for definition of symbols).

Growth stage (GS)		**GS-I**				**GS-II**			**GS-III**			**GS-IV**	
DAP		**23**	**33**	**37**	**41**	**54**	**58**	**70**	**81**	**86**	**105**	**127**	**138**
Rainfall (mm)		19.8	14.1	6.5	25.9	12.7	22.3	10.5	7.9	10.6	10.6	7.4	14.7
P_i Peak (mm h^{-1})		30.0	46.8	6.0	14.4	4.8	30.0	14.4	44.4	24.0	24.0	28.8	10.8
Duration (min)		630	320	245	1200	960	565	300	60	140	125	205	555
		Ro (mm)											
RSL-1	ML0%	5.7	6.1	0.9	3.1	1.1	7.9	2.5	1.8	3.2	4.3	2.3	3.1
	ML39%	4.3	4.9	1.1	2.8	1.3	2.4	1.0	1.6	1.3	1.9	1.2	2.4
	ML96%	3.6	4.4	0.8	2.9	0.9	2.1	1.4	1.3	1.0	2.4	1.9	2.2
RSL-1.5	ML0%	4.1	3.2	0.4	2.6	0.6	3.5	1.3	1.8	1.3	2.1	1.3	2.2
	ML39%	4.0	2.6	0.5	2.1	0.8	2.8	0.7	0.8	0.9	1.4	0.8	1.4
	ML96%	3.3	2.8	0.7	1.9	0.7	2.0	0.8	1.3	0.7	1.3	1.2	1.4
RSL-2	ML0%	3.1	3.5	0.5	2.1	0.7	4.4	1.9	2.1	2.0	3.4	2.2	4.4
	ML39%	2.7	1.7	0.5	1.9	1.0	3.0	0.8	0.6	0.5	1.1	1.0	1.1
	ML96%	2.5	2.3	0.7	1.7	0.6	2.2	0.7	0.6	0.5	0.8	1.0	0.7
RSL-3	ML0%	2.5	2.0	0.2	**NA***	0.7	**NA***	1.0	2.0	2.3	3.4	1.5	2.3
	ML39%	1.8	1.3	0.3	0.8	0.4	3.1	0.3	0.3	0.2	0.8	1.0	0.4
	ML96%	1.7	0.9	0.1	0.0	0.0	0.0	0.0	0.2	0.0	0.4	0.4	0.2

**Events when the structure was broken by the force of the runoff water*

The measured in-field runoff from short runoff strip length (RSL-1) varied from 0.8 to 7.9 mm, while the runoff strip length of 1.5 and 2 m gave measured runoff in the range of 0.4 and 4.4 mm. However, the amount of runoff recorded from the wide runoff strip length of 3 m (RSL-3) was only between 0.0 and 3.4 mm, under different levels of mulch although the two largest rain events do not have measurements. The analysis of variance indicates that both RSL and ML treatments showed highly significant differences ($P < 0.0001$) at different growth stages during different measurement events (Table 3.3). However, the interaction effect of RSL and ML treatments had no significant effect on runoff at different duration of measurements (Table 3.3). The results show that each surface treatment on the runoff area has a significant effect on collectable runoff amount during the growing season (Table 3.3). The mean comparison in runoff strip length shows that the narrow (RSL-1) plots generate significant more runoff than the wide (RSL-3) plots. It is also noticeable that there was no significant difference of the amount of in-field runoff from 1.5 and 2 m long runoff strip length plots with a mean of 1.7 mm. The results show a large difference in runoff from 1 m and 3 m runoff strip lengths, with mean Ro from the narrow (RSL-1) treatment being nearly 3 times more than that from wide (RSL-3) treatment plots

Table 3.3 Analysis of variance of mean comparison, indicating the effect of runoff strip length and mulch level factors on in-field runoff (mm).

Treatments RSL	Treatments ML (mm)			mean
	0% (bare)	39% (2 t ha^{-1})	96% (5 t ha^{-1})	
RSL-1	3.6	2.2	2.1	2.6a
RSL-1.5	2.0	1.6	1.5	1.7b
RSL-2	2.5	1.3	1.3	1.7b
RSL-3	1.5	0.9	0.3	0.9c
mean	2.4a	1.5b	1.3b	
LSD:	ML= 0.30	RSL= 0.34	RSLxML= ns	

** means followed by the same letter are not significantly different (P< 0.05)*

In a study with runoff plots of 1, 2 and 3 m strip length in a maize field at Hatfield Experimental Farm of the University of Pretoria, on a sandy clay loam soil with 6% slope, Ibraimo (2011) found that runoff depth decreases with increase in plot length, while runoff efficiency showed a general decline. From that study, runoff efficiency from bare plots varied between 51% and 53%. Botha *et al.* (2003) reports an average in-field runoff efficiency of 43% from 2 m runoff strip length on clay soils with 1% slope on the Glen/Bonheim ecotope. In this experiment, the highest runoff depth of 7.9 mm (43% of rain event amount) was recorded on a bare (ML0%) and narrow runoff strip length of 1 meter. These results also confirm those of Bruggeman and Oweis (1998) who studied the effect of runoff strip length on runoff efficiency. In general, their in-field runoff was larger on narrow runoff strip length than wider strips, due to lower water storage capacity and surface friction in the narrow runoff strips.

Regarding the effect of mulching practices, measured in-field runoff amounts were highly variable with CV ranging from 5% to 65%, 11% to 38%, 11% to 98% and 22% to 153% for RSL of 1, 1.5, 2 and 3 m treatments, respectively. Nonetheless, the bare management harvested more in-field runoff water and showed a significant difference from 39% and 96% mulch level cover. Moreover, runoff was shown to increase sharply with bare and lower mulching levels compared to mulched treatments. The mean in-field runoff amount from bare plots increased by 38% and 46% from the 2 and 5 t ha^{-1} mulch covered plots. Botha *et al.* (2003) found that the average runoff from the mulch plot was nearly 7 and 10 times less than bare plots on the Glen/Bonheim ecotope (clay soil) and Glen/Swartland ecotope (fine sandy clay soil), respectively. From their three year study Botha *et al.* (2003) concluded that organic mulch of reeds produced the greatest reduction in runoff, compared to bare plots. The runoff measurements were made on 2 m and 3 m long plots in the absence of a crop and with a reed mulch (60%) covering the flat crusted runoff surface. From a runoff study of cropped and uncropped plots, Lal (1998) found that the lowest runoff amount was generally observed for high mulch levels of 4 t ha^{-1}. His measured annual runoff ranged from a low of 9.5 and 27.2% of rainfall for 4 t ha^{-1} mulch cover to a high of 16.3 to 54.6% for bare plots during two different measurement years. The second year runoff gave a greater percent than first measurement year, probably because of a decline in the infiltration rate due to surface sealing and crust formation. Moreover mulch application also alters the top soil physical properties which could affect the runoff processes during the rain events. As shown from other studies it is understood that mulching depth can increase infiltration in the runoff strip by disruption of surface crust and can create depressions for temporary storage of water (Unger, 1992).

3.3.3 Predicting runoff as a function of rainfall and cultural practices

In order to develop runoff-rainfall relationships for different surface treatments, Ro regressions were made using rainfall event amount, duration and intensity so as to include these rainfall characteristics in the final equation. However, in all cases the data are highly scattered and not closely related to individual variables, with very weak coefficient of determination values, despite Ro measurements showing different trends according to different RSL treatments with the range of ML cover (see 3.3.2). However, for future studies one wants to be able to provide a reliable estimation of Ro, so a multiple regression analysis was performed to develop this Ro estimation using combined effects of rainfall variables and cultural practices.

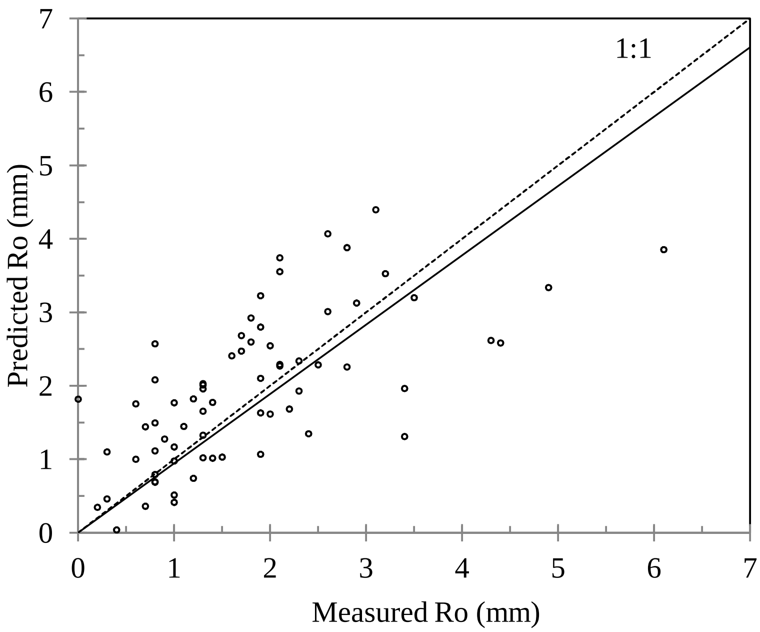
Linear regression models were used for prediction and evaluation of the effects of the different parameters of cultural management practices and rainfall characteristics (rainfall event amount, peak intensity, mean intensity, median intensity, rainfall event durations, growth stages, days after planting, mulching level cover and runoff strip length) on the amount of runoff generated. After checking various combinations, stepwise regression analysis produced the following multiple linear regression using only half the dataset (n=71):

$$Ro = 1.023 + 0.138RF + 0.033Pi - 0.654RSL - 0.013ML \qquad \textbf{3.1}$$

where Ro=measured in-field runoff amount (mm), RF=rainfall amount during rain event (mm), ML=mulch level (%), RSL=runoff strip length (m) and Pi=peak rainfall intensity (mm h^{-1}).

From this result it is seen that runoff could be fairly well predicted by a regression model with a coefficient of determination (R^2) equal to 0.69 and significant at $P < 0.001$ level. According to this analysis, runoff is significantly affected by these four parameters namely: amount of rainfall, mulch level, runoff strip lengths and peak rainfall intensities. The model shows that the main characteristics of the rainfall event (amount and peak intensity) are positively related to Ro, whereas an increase in runoff length and addition of mulch cover both reduce in-field runoff water. Furthermore, by comparison across treatments the rainfall characteristics were found to correlate better with the runoff amount in bare and narrow RSL treatments than in wide RSL with a 96% mulching level. This could be due to the effect of the runoff soil surface destabilization by the excessive rain droplet impacts. Therefore, it is suggested that using the selected rainfall characteristic variables and surface treatments in the derived multiple linear regression model could be useful to predict in-field runoff during the growing season.

The performance of the model depends on how well Ro predicted values agree with measured values. The verifying exercise (using other half of the data) yielded good results (D=0.97) for the model reliability tests using Willmott index (1981; 1982). The scatter plots indicate that the model can estimate runoff with statistical acceptable values during the growing season under the system of IRWH (Fig. 3.1).



n	71
RMSE	0.89
RMSEs	0.45
RMSEu	0.77
MAE	0.71
R^2	0.48
D-index	0.97
slope (b)	0.63
intercept (a)	0.79
RMSEs/RMSE	0.51

Figure 3.1 Scatter plot of the measured versus predicted in-field runoff for the growing season 2008/09.

The R^2 value (0.48) is not very good but the D index value (index of determination, 0.97) and RMSEs/RSMS (0.51) are both fairly good and acceptable, showing that deviation from the measured value was random. The systematic error (RMSEs=0.45) for the model is less than RMSE (0.89) and the unsystematic error as a ratio of RMSE (RMSEu/RMSE=0.86) was acceptable, indicating that the deviation from the measured values was random. Therefore the statistical test of the verifying procedure provides relatively satisfactory results with MAE value of 0.71 mm over the growing period.

3.3.4 Long-term in-field runoff predictions

The equation developed above (Eq. 3.1) was applied to estimate the water that could be generated through in-field runoff for each rain event during 15 of a crop growing seasons (1992-2007) at Glen (28^{o}56’S, 26^{o}20’E, 1304 m). The highest and lowest total rainfall of a growing period (Dec – May) was recorded as 565 mm and 186 mm with an average growing season rainfall of 313 mm. The predicted Ro increases linearly with amount of rain received but with a steeper curve on the bare surface than the full mulch cover (Fig. 3.2). This result only used rain events greater than 1 mm and less than 40 mm.

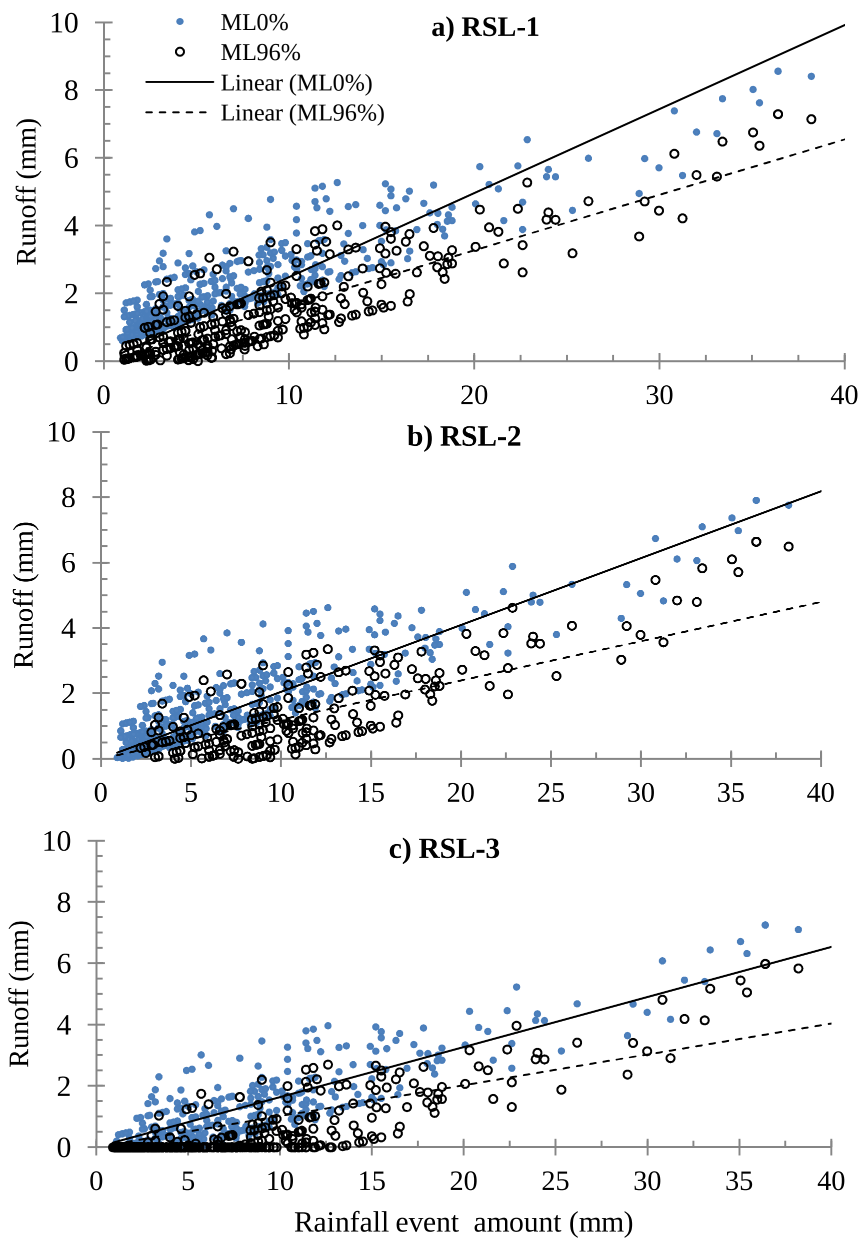


Figure 3.2 Relationships between rainfall event amount and predicted in-field runoff during the 15 years of the cropping season (n=576) for two mulch levels and three runoff lengths a) RSL-1, b) RSL-2 and c) RSL-3 for Glen Agricultural College, Rainfall dataset (1992 - 2007) from ARC-ISCW.

As shown in Fig. 3.2, the bare treatment on all lengths (RSL treatments), gave relatively higher Ro amounts from the rain events than when the full mulch was simulated, but they follow the same trend of increased Ro with increased rainfall. As the amount of rain increased, the predicted Ro was less widely scattered but the R^2 in all cases were reasonably acceptable enabling Ro to be estimated from the rainfall. The linear relationships between rainfall event amount and Ro predicted for the surface treatments were as follows:

RSL-1:	MR0%	$Ro = 0.2482RF$	(R^2= 0.69)	**3.2**
	MR96%	$Ro = 0.1635RF$	(R^2= 0.80)	**3.3**
RSL-2:	MR0%	$Ro = 0.2045RF$	(R^2= 0.84)	**3.4**
	MR96%	$Ro = 0.1199RF$	(R^2= 0.58)	**3.5**
RSL-3:	MR0%	$Ro = 0.1633RF$	(R^2= 0.84)	**3.6**
	MR96%	$Ro = 0.1008RF$	(R^2= 0.70)	**3.7**

where Ro is predicted in-field runoff and RF is rainfall event amount.

From these linear models, as shown in Fig. 3.2, the highest R^2 (0.84) was obtained from the bare plots on RSL-2 and 3 treatments, while the lowest R^2 (0.58) was observed for full mulch cover of RSL-2. However, the slope of the linear fitted lines can represent the proportion of the rainfall that producing runoff for varying surface treatments under IRWH.

These results accentuated that; firstly, under the technique of IRWH, with a narrow bare runoff strip it is possible to harvest higher amounts of Ro water (24%) compared to a wide fully mulched runoff strip (10%). Secondly, from the graphs, it can be seen that the concentration of data points at zero Ro increased on the longer runoff strips with 96% mulch (Fig. 3.2). This shows the importance of the small rain events in producing in-field runoff under varying surface treatments. Many long-term statistical models (Hensley *et al.*, 2000; Walker and Tsubo 2003a; Zere *et al.*, 2005; Welderufael *et al.*, 2008) excluded small rain events in order to obtain a realistic Ro amount. However, Anderson *et al.* (2007) concluded that statistical models provide a better estimation of runoff at low rainfall amounts, as their R^2 using all data points were generally considerable better than those with only rain amounts greater than 8 mm. Thus, it is considered that for long-term prediction the inclusion of small rain events is a valuable asset for IRWH system.

With this knowledge of rainfall-runoff relationships an investigation of rainfall event distribution (Walker and Tsubo, 2003a) is an important factor for runoff simulations. By analyzing probability curves for in-field runoff processes during a crop growing period, probability density functions in a range from zero to one can be used to describe the distribution of runoff increments with increasing rainfall amount. Thus, the cumulative probability functions (CPF) describe the long-term simulated in-field runoff from different surface treatments for the technique of IRWH for 15 years (1992 – 2007) data set at Glen (Fig. 3.3).

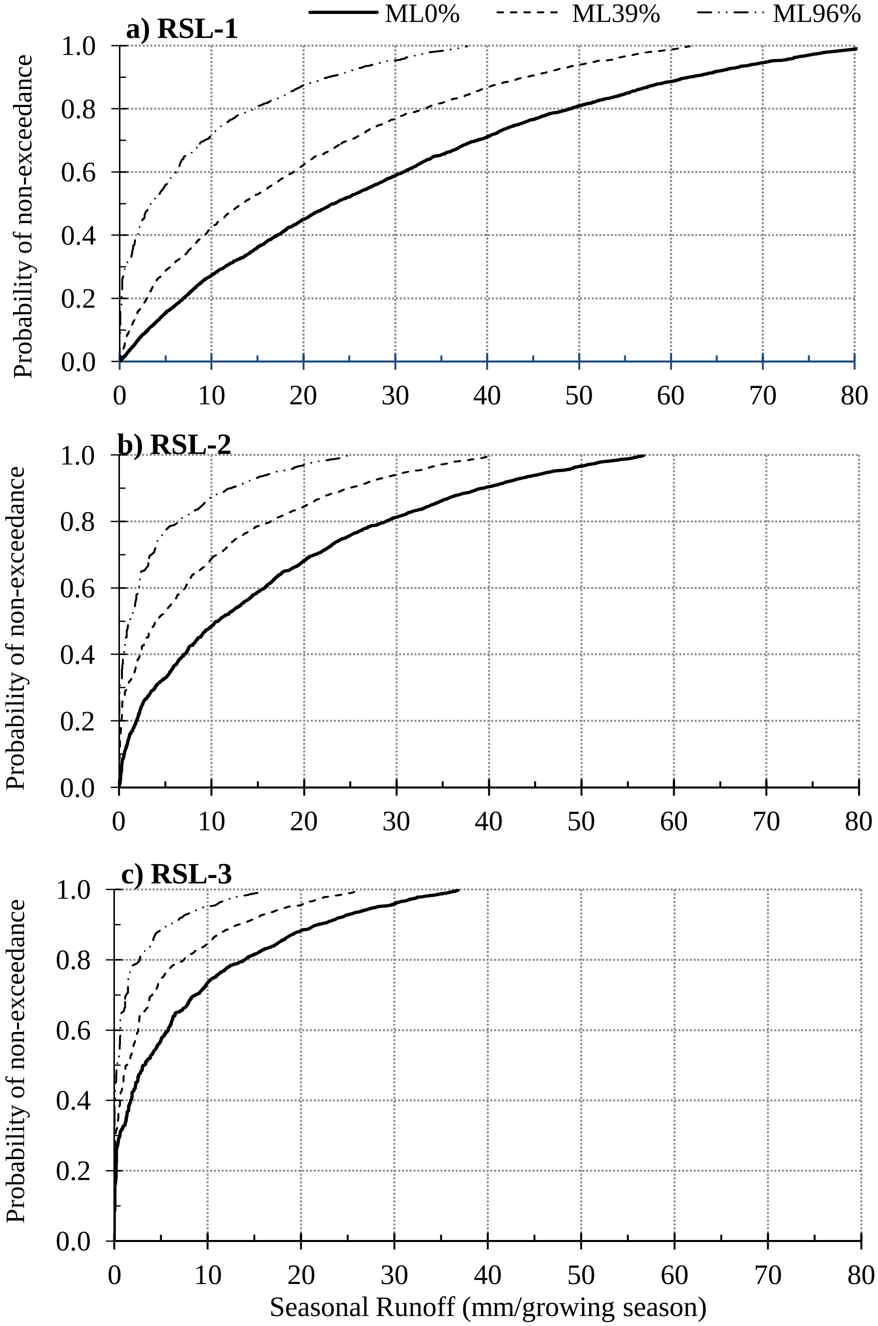


Figure 3.3 CPFs of predicted long-term runoff during the maize growing season (December to May) from RSL-1, 2 and 3 m length strips with different mulch cover treatments. Rainfall event amount data used are for 15 years (1992 – 2007) at Glen, ARC-ISCW.

CPF graphs of simulated long-term Ro on RSL-1, 2 and 3 with varying mulch levels were compared at 80% and 40% probability levels. The data sets showed significant differences ($P < 0.05$) between the mulch levels and higher values were found for the bare as compared to mulched treatments. The bare plots have an 80% probability to generate in-field runoff water into basin area of 48, 28 and 14 mm per growing season from runoff strip length of 1, 2 and 3 m treatments, respectively. By comparison with mulch cover, the bare treatments have considerable advantage in supplying more water to the basin area. At 80% probability level the bare plots contribute more rainwater with an advantage of 16 & 33 mm, 12 & 21 mm and 7 & 11 mm into basins for RSL-1, 2 and 3, respectively over the mulch cover plots of 2 and 5 t ha^{-1}.

At 40% probability, the predicted amount of in-field runoff harvested from the wide (RSL-3) with full mulch (96%) cover is insignificant. At this level of probability, the mulched plots have a possibility to infiltrate the rainwater on the runoff strip and restrict the inflow of runoff towards the basin area. Therefore, in general terms the predicted amount of in-field runoff collectable water from a bare narrow (RSL-1) has more advantage for infiltration in the basins, while wide strips (RSL-3) with full mulch (96%) cover infiltrate more the rainwater on the runoff strips. The physical property of the soil of the experimental site attributes a high infiltration rate on the bare plots. This meant that the fine sandy loam soil with gentle slope (<1%) of the experimental site enhance infiltration due to soft crust formation on the top soil surface. This implies that the soil has an ability to hold considerable amount of water after a rain event, that will support crop production. In addition the mulch cover on the runoff area modifies the soil structure underneath and reduces the in-field runoff into basin area. Botha (2006) mentioned that both the rainwater harvested into the basin area and infiltrated on the runoff strip contribute to the crop yield response. However, the rainwater harvested into basins has an advantage during the early growth stages when less roots present and the reserved water under runoff strip becomes available to the crop when the maize root ramification reached maximum at flowering/tasseling stage.

3.4 Conclusion

From the field runoff measurements, it was possible to assess and evaluate the influence of a mulch layer on the runoff strips with the in-field runoff water harvesting technique. The practical measurements of runoff provided information about which rain events received during the growing season generated varying amounts of runoff, and the amount of runoff generated was found to vary according to the rainfall characteristics (rainfall event amount and peak intensity) and surface treatments (RSL & ML).

The decrease in runoff from the addition of mulch also depends on the length of runoff strip. Considering the whole season, highest runoff (43% of rain amount) was recorded on a bare (ML0%) and narrow runoff strip length of 1 m and the lowest amount was observed from wide (RSL-3) completely covered with mulch (ML96%). The rainwater harvested to the basin area has an advantage for the direct use by the crop. Increasing runoff strip cover with mulch decreases in-field runoff to the basin and presumably increases infiltration across the runoff area. This will provide enough rainwater storage to carry the maize crop through dry spells, in particular during flowering/tasseling stage. Therefore, the fine sandy loam soil at Kenilworth Experimental Farm has been shown to be suitable for the technique of IRWH, due to the ability of the soil profile to hold rainwater following a wet period and to be accessed by the roots during short dry spells.

The simulated runoff using the stepwise regression model showed that the amount of runoff generated by a given area depends on the rainfall characteristics and surface agronomic treatments. The regression model for runoff simulated during the rain events gave good agreement, with coefficient of determination (R^2) of 0.69 being significant at 1% level. An important result is that this equation was developed to predict in-field runoff by combining the effects of rainfall event characteristics and cultural management practices for the IRWH system. The derived equation was also used with long-term rainfall amounts to predict the in-field runoff potential from different surface treatments. The result confirms that at any probability levels the bare plots can contribute the highest additional rainwater to the basin area, and that wide fully mulch plots infiltrate more rainwater on the runoff area.

CHAPTER 4

Effect of Surface Treatments on Rainfall Canopy Interception, Runoff-Rainfall ratio and Infiltration Ratio for In-field Rainwater Harvesting

4.1 Introduction

Agricultural crop management practices have a major impact on partitioning of rainfall into canopy interception and runoff or infiltration components. Runoff is generated by rainstorms and its occurrence and quantity are dependent on the characteristics of the rainstorm event as well as crop management practices. In the in-field rainwater harvesting (IRWH) system the most important factors which influence the runoff generating process apart from rainfall characteristics are: the catchment characteristics which include runoff strip length (RSL), vegetation and surface cover, textural properties of the soil and slope of the area (Bruins *et al.*, 1986). Each runoff producing area has its own runoff response that will respond differently to different rainstorm events. Moreover, the concept of the capacity of the crop canopy to intercept some rainfall and hold water must be considered before the rain reaches the soil or mulch covered surfecs.

The partitioning of rainfall into canopy interception, runoff and infiltration components needs to be catered for, especially in the system of IRWH. It is crucial to understand what part of the rain that falls on the runoff and basin strips is effectively reaching the crop roots. In many cases, IRWH studies are conducted on crop fields, but rainfall canopy interception (RCI) losses are excluded. This affects the amount of water reaching the root zone. These significant interception losses may result from the many small rainfall events which are largely intercepted by the canopy (Wood *et al.*, 1998; Dunkerley, 2000). A two parameter model, using rainfall amount and leaf area index (LAI), has been constructed (Linsley *et al.*, 1949; Merriam, 1960; Aston, 1979; Calder *et al*., 1996; Liu, 2001; Wang *et al*., 2005) to describe the RCI processes. For example, for modelling runoff in a maize cropping system Laloy and Bielders (2008) applied the Aston (1979) and Hoyningen-Huene (1981) equations to estimate the rainfall interception and maximum canopy storage as a function of leaf area index. The research illustrated the relevance of continuous runoff modelling throughout the rainfall events by incorporating the RCI.

Surface management of the runoff strips of IRWH have varying response to specific rain events. That is the reason why the water harvesting techniques require the knowledge of the quantity of the runoff amount in relation to the specific rain event. However, continuous measurement of in-field runoff to investigate the influence of runoff processes during crop growing period is difficult and tedious (Boers and Ben-Asher, 1982). Therefore, it is commonly assumed that the quantity of runoff per unit area is a proportion of the rainfall depth (Boers *et al.*, 1986); Chapter 3, Section 3.2.4. On a seasonal basis, runoff amount is reported to be linearly related to rainfall depth (Boers *et al.*, 1986; Hensley *et al.*, 2000; Botha, 2006; Ibraimo, 2011). They suggested that this relationship could also be applied for individual rain events. In contrast, Karnieli and Ben-Asher (1993) found that the relationship between rainfall and runoff was non-linear. Kinnell (1996) and Woyessa and Bennie (2004) described that the importance of relating the amount of runoff in the form of a ratio of the total runoff to the rainfall during the growing period.

The knowledge of in-field runoff from individual rain events is essential to evaluate the runoff behaviour for different runoff strip lengths and mulching level practices. However, a determination of total runoff during the growing season should form part of the justification of improved cultural management practices. The approach of using runoff to rainfall (RR) ratio and estimations of RCI can be used to optimize runoff to basin area ratios for IRWH. All runoff studies conducted on IRWH in South Africa ignored interception by the crop. This is a very important factor influencing the optimizing of basin to runoff area ratio and the fraction of rainwater available to infiltrate in the basin from run-on. Therefore, this study was undertaken with the hypothesis that the RCI will increase as the length of runoff strip increases and hence reduce the amount of water reaching the basins. This will have an influence on the total run-on to the basins and the amount that will potentially infiltrate in both the runoff and basin areas. Therefore, the objectives of the study were:

- to evaluate RCI under different runoff strip lengths of IRWH, theoretically;
- to quantify the effect of surface treatments (RSL and ML) on RR ratio; and
- to determine the partitioning of rainwater falling on the runoff strips and basins, and the fraction of rainwater available to infiltrate in the system of IRWH.

4.2 Materials and methods

4.2.1 Procedure for estimating rainfall canopy interception

4.2.1.1 Theoretical basis

The RCI (mm) was estimated per rain event by applying the equations of Aston (1979), de Roo *et al.* (1998) and Von Hoyningen-Huene (1981) for a maize canopy under IRWH:

$$RCI = S_{max} \times \left[1 - e^{-(1-P\prime)\frac{RF_{event}}{S_{max}}}\right] \qquad \textbf{4.1}$$

$$S_{max} = 0.935 + 0.498 \times LAI - 0.00575 \times LAI^2 \qquad \textbf{4.2}$$

where RF_{event} is the rainfall event amount which representing a group of rainstorms as explained in Chapter 3 (Section 3.2.1), P' is a correction factor (P'= 1-0.046×LAI), S_{max} is the maximum amount of rain that the canopy of the crop can intercept (mm) and LAI = the leaf area index.

The *P*' factor incorporates the process that only a part of a rainfall event which falls on the canopy can contribute to the interception storage. The specificity of this method is that it allows some rainfall to reach the ground at the same time as the interception capacity is being filled (Hoyningen-Huene, 1981). It was assumed that all rain arrives vertically and all plant parts in the inter-rows behave rigidly and arranged alternatively to intercept water in the canopy.

4.2.1.2 Application

With above assumptions in mind, Equations 4.1 and 4.2 were applied to all bare runoff surface treatments from the main experiment described in Chapter 2, Section 2.2. Thus, the 1 m, 1.5 m, 2 m and 3 m wide runoff strip length treatments without mulch were selected for the RCI analysis. The analysis was purely based on the surface area of the basin where maize was planted in a tramline along the 1.1 m width basin as indicated in Fig. 1.2. In order to obtain a similar plant density per plot (basin and runoff area), irrespective of other treatments, the inter-plant distance was adapted according to the plot area (see Chapter 2, Section 2.3.3 and Table 2.3 for detail). The resulting plant densities per unit basin area were 3.3, 4.1, 4.9 and 6.4 plants m^{-2} for the 1, 1.5, 2 and 3 m RSL treatments, respectively.

Equation 4.2 requires a LAI, which was obtained from the leaf area measurement made on the mentioned treatments (see Chapter 2, Section 2.4.4.1 for details on the method). However, leaf area measurements were made at a 10 day interval from 25 days after planting (DAP) until the crop attained maximum size at 65 DAP. The leaf area was expressed per unit area of the basin area ratio called BLAR (see Section 6.2.2), i.e. to represent leaf area, and the values for the different treatments are listed in Table 4.1.

Table 4.1 Observed basin leaf area ratio (BLAR) values for different RSL treatments on a bare soil during maize growing season 2008/09.

RSL treatments	Plant density (plants m^{-2})	Time after planting (days)				
		25	35	45	55	65
1 m	3.3	0.06	0.10	0.46	0.98	1.11
1.5 m	4.1	0.09	0.12	0.38	1.22	1.43
2 m	4.9	0.09	0.20	0.65	1.48	1.64
3 m	6.4	0.10	0.25	0.74	1.90	2.38

Another parameter that was required in the estimation of RCI is RF_{event} (Equation 4.1). The RF was obtained from the weather data rainfall event (see Table 3.2). Each event when runoff was possible, regardless of durations or time step. RCI was calculated for each rain event and summarized in Appendix 4.1.

4.2.1.3 Experimental design and statistical analysis

The RCI results in Appendix 4.1 were further evaluated: firstly, to determine the impact of growth stages (GS) on RCI. The RCI values, express per rain event, were therefore summed for each of the four GSs used, *viz.* the vegetative (GS-I), late vegetative to tasseling (GS-II), tasseling to grain-filling (GS-III) and grain-filling to maturity or harvesting (GS-IV). Thus, the experimental design comprised the four RSL-bare treatments (1, 1.5, 2 and 3 m runoff strip lengths) in combination with four GS (GS-I, GS-II, GS-III and GS-IV). The statistical analysis was performed with SAS 9.1.3 for Windows (SAS Inst. Inc., 2006) using a two way factor interaction (RSL × GS) with no replications. The main reason for un-replicated analysis was due to RCI estimation not being dependent on the runoff experiment, as it only used the rainfall events during the growing season 2008/09 which were assumed to be the same across the whole experiment.

The second evaluation of RCI was aimed to understand how RCI is influenced by rainfall characteristics under IRWH. For this analysis the RCI values in Appendix 4.1, express per rain event, were regressed against rainfall amount and also rainfall duration. Only the 1 m and 3 m

RSL treatments were used to demonstrate the basic principles involved. In order to statistically analyse, empirical relationships were derived using regression procedures.

4.2.2 Procedure for estimating runoff-rainfall ratio

4.2.2.1 Theory

The runoff to rainfall (RR) ratio is a general expression to obtain the fraction of runoff generated as a function of the amount of rainfall (Woyessa and Bennie, 2007). The RR ratio was determined for a single rainfall event (RF_{event}) or for the whole growing season. For the single rain event the following relationship is used:

$$RR = \frac{Ro}{RF_{event}} \qquad \textbf{4.3}$$

where Ro is represents runoff measured from the runoff strips during a rainfall event (RF_{event}).

For the growing season the individual runoff amounts and rainfall event amounts were summed (∑). This was termed the total runoff–rainfall (TRR) ratio:

$$TRR = \frac{\sum R_o}{\sum RF_{event}} \qquad \textbf{4.4}$$

4.2.2.2 Application

Due to physical and financial constraints the runoff experiment was only conducted on three ML (0%, 39% and 96%) treatments in all RSL treatments. In order to obtain a wider ML versus RR relationships a runoff mulch factor (RMLF) was introduced. This was expressed as the ratio of total runoff from the mulched ($\sum Ro_{mulched}$) to the bare treatments ($\sum Ro_{bare}$):

$$RMLF = \frac{\sum Ro_{\,mulched}}{\sum Ro_{bare)}} \qquad \textbf{4.5}$$

From above it is clear that the application of Equations 4.3 and 4.4 requires the measurement of in-field runoff and rainfall. Equation 4.5 was also utilized to apply an approach of mulch application factor effect (RMLF) to interpolate the effect of each ML treatment (including those not measured, ML12% and 64%). The measurement of in-field runoff was made on the runoff plots between 05 January and 07 May 2009, a period which included rainfall events during different crop growth stages. The overall procedures of in-field runoff measurements and the approach used to calculate the amount of runoff are described in Chapter 2, Section 2.4.2.2 and Chapter 3, Section 3.2.3. The method for measuring RF was described in Chapter 2, Section 2.4.1.

4.2.2.3 Experimental design and statistical analysis

RR ratio was calculated for each of the runoff plots. The experimental layout of the runoff plots is available in Chapter 3 Section 3.2.1. For the RR ratio analysis, the experimental design comprised four RSL treatments (1 m, 1.5 m, 2 m and 3 m) combined with three mulch level (ML) treatments 0%, 39% and 96%. The experiment was un-replicated, but repeated over each rain event. Thus, a two way factor interaction split plot arrangement as described by Sokal and Rohlf (1981) and Box and Jones (1992) was adopted for the statistical analysis. Mean separation was achieved by applying the LSD test. A probability level of 5% was designated for significance differences. The analysis was done with SAS 9.1.3 for Windows (SAS Inst. Inc., 2006).

For the relationships of RR ratio and surface treatments a simple regression procedure was applied. In addition for the ML - RR linear relationships, the slopes of the lines were computed with a statistical method using a Graphpad Prism 5 (Graphpad Software, 2007), besides it is also true that, the intercepts establishing RSL - RR ratio relationships over the combined mulch level effects.

4.2.3 Procedure for estimating infiltration

Infiltration in the runoff area (I_{RA}) and basin area (I_{BA}) was estimated with Equations 4.6 and 4.7, respectively:

$$I_{RA} = RF - R_{on} \qquad \textbf{4.6}$$

$$I_{BA} = RF + R_{on} - RCI \qquad \textbf{4.7}$$

where RF is the rainfall event (mm) and R_{on} the amount of water collected in the basin area and RCI the rainfall canopy interception (mm).

The amount of water collected in the basin (R_{on}) was depending on the length of runoff strips. This meant that for every RSL treatment, the R_{on} amount should be a multiply of the length of the runoff strip. In other words, the R_{on} amount was obtained as a result of Ro multiplied by the length of the runoff strip for each treatment, *viz.* 1 m, 1.5 m, 2 m and 3 m for RSL-1, RSL-1.5, RSL-2 and RSL-3 treatments, respectively.

Infiltration was then express as an infiltration ratio, i.e. I_{BA}:I_{RA}, which indicates that for every unit mm of water that infiltrate in the runoff section, some additional mm of water will infiltrate in the basin area. RCI is associated with the basin area as explained in Section 4.2.1. The calculated infiltration ratio results were comprised of all RSL (1, 1.5, 2 and 3 m) and ML (0%, 12%, 39%, 64% and 96%) combinations. The statistical analysis for calculated I_{BA}:I_{RA} results were implemented by using SAS 9.1.3 for Windows (SAS Inst. Inc., 2006) using a two way factor interaction (RSL × ML) with no replications (as described in Section 4.2.2.3).

4.3 Results and discussion

4.3.1 Rainfall canopy interception

4.3.1.1 Effect of surface treatments

The results of RCI for the different RSL treatments showed variations during the growth stages (Table 4.2). The analysis of variance (n=16) revealed that there was no significant interaction between the two factors (RSL and GS), but the individual factors affected the RCI significantly ($P < 0.05$). Thus, only the effect of the main factors (RSL and GS) will further be discussed. Accordingly, the RSL results clearly showed that RCI increases with an increase in the length of the runoff strips; RCI at the 1 m and 1.5 m RSL treatments were both significantly lower than the 3 m RSL. This trend can be explained by the BLARs induced by the different plant densities in the basin area. The BLAR increased with an increase in the RSL treatments (Table 4.1), implying that the leaf surface available for interception of rain increases with an increase in the RSL. The statistics on the GS treatments showed that the RCI increased significantly from GS-I to GS-II, after which it stabilised (as GS-II was not significantly different from GS-III) before it decreases towards the last growth stage. This trend is attributed mainly due to the change in the surface area as indicated in Table 4.1. The results correspond with the general growth relationship of maize; LAI of maize will increase rapidly over the vegetative stage and will start to reach a plateau at tasseling (reproductive phase), where after it decreases during the ripening phase (Bennie *et al.* 1998; Tuzet and Wilson, 2002; Azam Ali and Squire, 2002). Todd *et al.* (1991) found that peak LAI for maize to be 60 - 65 days after planting at a range of 2.50 – 3.00 under dryland conditions. After a comprehensive investigation of the modelling on soil water components for semi-arid areas, Joseph *et al.* (2011) suggested that RCI generally decreases transpiration, infiltration and runoff. This implies that less water infiltrates into basin areas and it will be difficult to prevent these type of losses as it is related to rainfall characteristics such as the amount and duration as will be seen in the next section.

Table 4.2 Sum of rainfall canopy interception (RCI) by maize in basin area under IRWH as affected by runoff strip length (RSL) and growth stages (GS).

Runoff strip length (RSL)	Rainfall canopy interception (mm)					
	GS-I	**GS-II**	**GS-III**	**GS-IV**	**mean**	**Sum (∑)**
1 m	0.30	1.64	1.26	0.92	1.02b	4.12
1.5 m	0.29	1.99	1.59	1.15	1.26b	5.02
2 m	0.43	2.31	1.80	1.30	1.46ab	5.84
3 m	0.50	2.92	2.49	1.79	1.93a	7.70
mean	0.38c	2.21a	1.78ab	1.29b		
RF (mm)	66.3	45.5	29.1	22.1		
***LSD*:**	RSL = 0.54		GS = 0.51		RSL x GS= ns	

ns = none significant; means followed by the same letter are not significantly different (P< 0.05)

4.3.1.2 Relationship with rainfall characteristics

The results of the relationships between rainfall event amount and RCI (Figure 4.3a) and rainfall duration and RCI (Figure 4.3b), provided new insights to the question of how runoff strip lengths effect evaporation losses from the crop's canopy during rain events under the IRWH system. Accordingly the relationships were described by a second order polynomial function resulting in coefficients of determination (R^2) of 0.77 and 0.56 for RSL-1 (narrow runoff strip length) for the rain event amount and duration, respectively. For the RSL-3 (wide runoff strip length) the coefficients of determination were 0.69 and 0.65, respectively. Irrespective of the RSL treatments, the curves showed clearly that the RCI increases with an increase in the rainfall amount towards about 20 mm of rain, where after that it decreases with an increase in rainfall. Similar trends were observed for the RCI to rainfall duration relationships; RCI increases with durations up to 10 hours and declines with any further increase in the duration of rain events on both the RSL treatments. The plateau of the RCI-rainfall relationships further indicates that the capacity for rainfall interception is about double in the wider runoff strips compared to the narrow runoff strips of IRWH; RCI varied between 0.5 – 0.6 mm for RSL-1 compared to 1.0 – 1.1 mm for the RSL-3 at the plateau of the relationships. The plateaus correspond with the canopy saturation phase of Gash (1979).

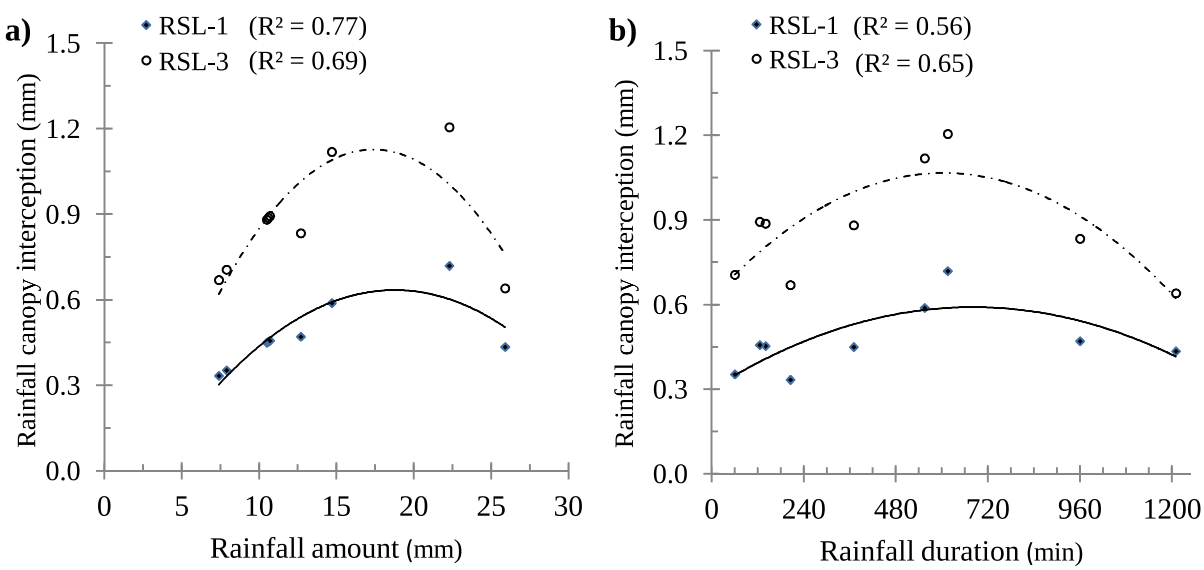


Figure 4.1 Rainfall canopy interception relationships with rainfall characteristics; (a) with rainfall event amount and (b) with rainfall duration. Polynomial fitting line with long dash-dot = RSL-3 and solid line = RSL-1.

It is also understood that the rainfall intercepted by the canopy would eventually evaporate or to some extent be drained and channelled to the surface after the canopy is once wetted (Wood *et al.*, 1998). van Dijk and Bruijnzeel (2001) estimate RCI losses for maize of 19% and 8% of total rainfall for a period of 124 and 196 days over the growing season, respectively. These simulated RCI values were to some extent at the top and above the range found here for the IRWH where values varied between 4.5% - 9% of the rainfall. However, the results demonstrate the importance of quantifying RCI in the tillage of IRWH as part of unproductive water for evaporation.

4.3.2 Runoff-rainfall ratio

4.3.2.1 Effect of surface treatments

Mulch treated runoff strips can modify the RR ratio of IRWH practised under semi-arid climate conditions, as proved by the statistical results of RR ratio presented in Table 4.3. Accordingly, the variation in the RR ratio over the experiment is high; stretching from 4% in RSL-3 ML96% to 27% in RSL-1 ML0%. The statistical results clearly show that the combined surface treatments (RSL × ML) affected the RR ratio significantly ($P < 0.05$ with LSD value of 0.037). This finding demands further examination. For this purpose the treatments were grouped into three levels of RR ratio efficiencies, *viz.* low (< 10%), moderate (10% - 15%) and high (> 15%). Interesting to note that, the lower efficiency group is associated with the widest runoff strip length covered with mulch, *viz.* RSL-3 ML39%, RSL-3 ML96%, and the 2 m runoff strip length covered almost fully with mulch (RSL-2 ML96%), although the statistical results revealed that the RR ratios of the RSL-3 ML96% treatment is significantly lower than that of the RSL-2 ML96% treatment. For RSL-3 ML39%, on the other hand, RR ratios did not differ from the other two treatments of this group. It can be concluded that these type of surface treatments illustrate that rainwater will rather infiltrate into the runoff strips than move towards the basin. Hence, mulch application on the 3 m wide runoff strip and full mulch cover on the RSL-2 is not a practical measure to promote harvesting water in the IRWH context. In contrast, Cattan *et al.* (2006) claimed that if the RR ratio were examined more closely, although a significant difference occurred between their bare and mulched plots, the maximum observed RR ratios were comparable. They suggest that in the event of heavy rainfall with high peak intensity the sheet runoff may mask the effect of the mulch. Nevertheless, the mulch might conserve water by restricting soil water evaporation as demonstrated by Botha *et al.* (2003) for IRWH. This principle was also demonstrated for other conservation tillage practices (Bennie and Hensley, 2001; Hensley *et al.*, 2000: Bothma, 2010; van Rensburg, 2010).

Table 4.3 Mean runoff to rainfall (RR) ratios calculated from measured runoff for the runoff strip length (RSL) and mulch level treatments under IRWH for 2008/09 (n=144).

Runoff strip length (RSL)	Mulch level (ML as %)		
	0%	39%	96%
1 m	0.27a	0.16c	0.17c
1.5 m	0.15c	0.11de	0.11de
2 m	0.21b	0.10ef	0.08ef
3 m	0.15c	0.06fg	0.04g
LSD:	RSL × ML = 0.037		

*m*eans followed by the same letter are not significantly different (P< 0.05)*

The moderate RR ratio efficiency group comprised five treatment combinations. In this group, the lower RR ratio efficiency treatments are connected to the mulch treated surfaces in combination with the 1.5 and 2 m runoff strip lengths, *viz.* RSL-1.5 ML39%, RSL-1.5 ML-96% and RSL-2 ML39%. The other two combination treatments in this group had a bare surface on the runoff strips (RSL-1.5 ML-0% and RSL-3 ML-0%). Both RR ratios amounted to 15%, which is significantly higher than those of the other three mentioned treatments. Compared to the first RR ratio efficiency group, the moderate efficiency group should probably exhibit a better balance between water harvested in the basin and water conserved through reducing evaporation on the runoff strips.

The high RR ratio efficiency group, *viz.* RSL-1 ML0%, RSL-1 ML39%, RSL-1ML96% and RSL-2 ML0%, is dominated by the 1 m long runoff strip length combination treatments. Comparing these treatments suggests that the RR ratio increases with a decrease in the percentage mulch coverage over the 1 m runoff strip. The significance of this trend lies in the fact that the RR ratio of the bare surface (27%) is significantly higher than the two mulched treated surfaces. Similarly, the RR ratio of the RSL-1 ML0% treatment was also significantly higher than the standard IRWH treatment (RSL-2 ML0%), which amounted to 21%. From the above results it can be concluded that a bare surface, irrespective of runoff strip length, has a great potential for water harvesting within IRWH.

4.3.2.2 Relationship with surface treatments

To relate different effects of runoff strip lengths on the amount of runoff, an approach of mulch application factor effect (RMLF) was adopted. The RMLF renders the relative effectiveness of mulch cover in reducing the amount of runoff to be harvested, but it can also be influenced by the length of the runoff strip, as experienced in this particular experiment. So that, to establish the relationship between all mulch levels and mulching factor runoff strips of different lengths were utilized *viz.* RSL-1, RSL-2 and RSL-3. The data fitted to an exponential decline, produced a strong coefficient of determination over the treatment RSL-3 and fairly well correlated with the treatments of RSL-1 and RSL-2 (Appendix 4.3). As cited by Zuzel and Pikul (1993), Wischmeire (1978) proposed an effective approach of a mulching factor method for reducing runoff and soil loss studies. Woyessa and Bennie (2004) found declined exponential relationships between mulching factor and residue cover; Gilley *et al.* (1986) also obtained an inverse exponential relationship of the percentage surface cover of sorghum and soybean residues.

Furthermore, in this study, in order to infer the relationship for all mulch levels on different RSL treatments the linear fitted lines were explained statistically through the provided slopes and intercept values. Surface treatments of IRWH have a distinct relationship with the RR ratios. This statement can be explained by the linear relationships between MLs and the RR ratios for RSL 1 m, 2 m and 3 m in Fig. 4.2. The data in Fig. 4.2 fitted well to a linear equation and two important features can be developed from these regression statistics.

Firstly, the slopes: the slopes were not significantly different ($P \leq 0.05$), which implies that an average slope will represent the effect of mulch cover on RR ratio for IRWH. Thus, it can be suggested that mulch causes the RR ratio to decrease at a rate of 0.065 per unit coverage (%), irrespective of the length of the runoff strips. This has a huge implication for future IRWH runoff studies. It means that it is not necessarily to conduct mulch level trails on different runoff strip length treatments. RR ratio results from mulch level treatments from zero tillage experiments can be used for predicting RR ratio on IRWH. A good example is the extensive runoff research that was done for red and yellow soils covered with maize residue in South Africa (van Rensburg, 2010). Recalculating the relationship between RR ratio and mulch cover for runoff measurements by McPhee and Smithen (1985) gives a slope of (0.44). A factor that needs to be taken into account is the type of mulch used. For example, Botha *et al.* (2003) showed that stone mulch induces significantly higher runoff than the organic reeds for similar surface coverage of the mulches.

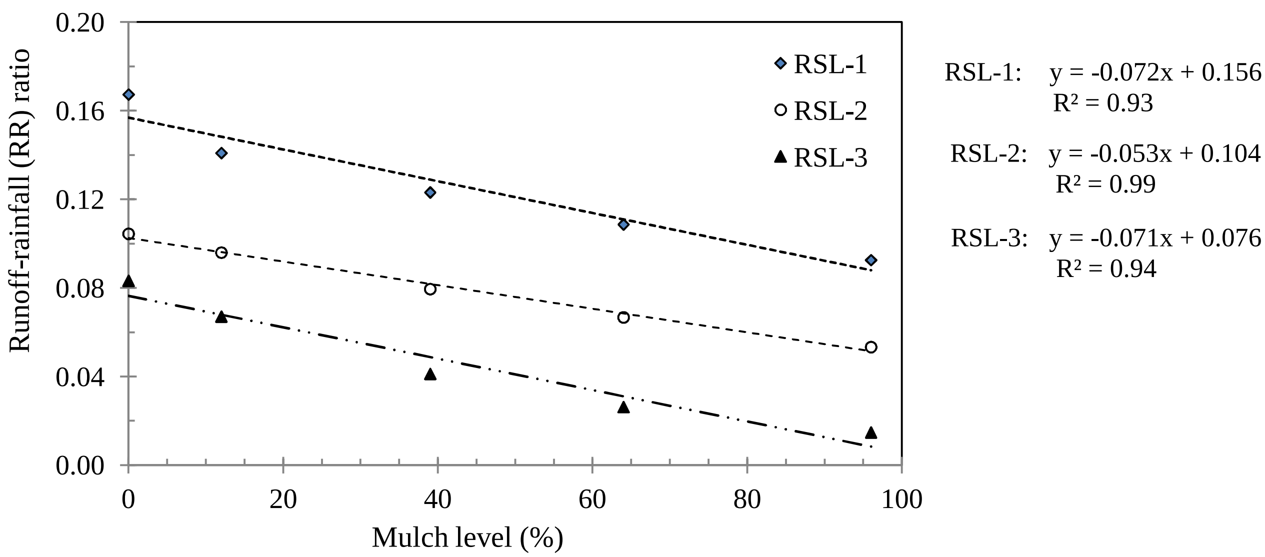


Figure 4.2 Runoff-rainfall ratios as a function of mulch level (%) on runoff strip lengths of 1 m, 2 m and 3 m. Linear lines: dotted = RSL-1, dash = RSL-2 and long dash-dot = RSL-3.

A second conclusion can be derived from the intercept of the linear equations in Fig. 4.2. The intercepts differ significantly from each other; suggesting that length of runoff strip is an important factor when left bare. In this case, the RR ratio decreases with an increase in the RSL as indicated in the linear relationship between RR ratio and RSL in Fig. 4.3. Thus, it is understood that, with an increase in length of the runoff strip, the amount of water to be harvested as a ratio of rainfall was reduced. The results of Kenilworth are strictly different in terms of amount and the degree of RR ratio variation among the treatments compared to those values measured at University of Pretoria's experimental field (Ibraimo, 2011). From the data points in Fig. 4.3, it is clear that the RR ratio of Kenilworth were only about 31%, 22% and 12% of the observed RR from Pretoria, for RSL of 1 m, 2 m and 3 m, respectively. Closer inspection reveals that the rainfall parameters (amount intensity and duration) as well as the surface properties (slope, texture and structure) of the soils differ widely. The infiltration capacity of Kenilworth Bainsvlei (9 mm h^{-1}) is higher than that of the Pretoria experimental field mainly due to a sandier texture (sandy versus clay loamy), presumably a lower roughness index (clay soils tend to decrease under rain drop impact forming a flatter runoff area, Botha *et al.*, 2003), and a lower slope at Kenilworth (1% versus 6%). These results illustrate that in-field runoff is complex and RR ratio cannot be extrapolated to other ecotopes without taking into account the rainfall characteristics and surface properties.

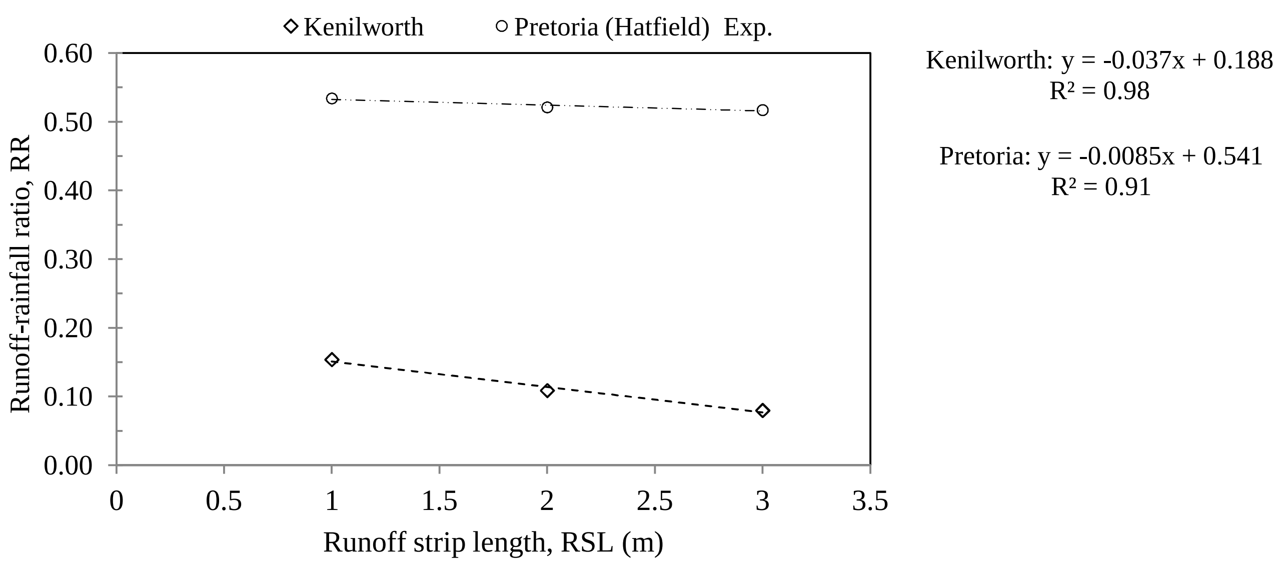


Figure 4.3 Comparison of RR-RSL relationship obtained at Kenilworth and Pretoria (Ibraimo, 2011) experiments. Line with dash = Kenilworth exp. and long dash-dot = Pretoria (Hatfield) exp.

The above statements can be confirmed by comparing the RR results from bare RSL 2 m (standard runoff strip length) at Kenilworth with other ecotopes. For the typical example from

Glen/Bonheim with dark brown clay soils (45% clay) and the fine sandy clay of Glen/Swartland (38% clay) with a similar slope of 1%, Botha *et al.* (2003) found a RR ratio of 0.43 and 0.39 respectively. In another ecotope at Thohoyandou in Limpopo Province, on red clay soil (60% clay) with a high water holding capacity, Mzezewa and van Rensburg (2011) reported higher runoff values than those of Glen and much higher than the Kenilworth experiment (8.5% clay). The main factors enhancing runoff, as reported by Mzezewa and van Rensburg (2011) steeper slopes (8%) where largely attributed to higher RR ratio compared to the very gentle slopes (< 1%) of this experiment (RR ratio ≈ 0.104). On the other hand, the two different sites at Glen, with the application of different types of mulch cover on 2 m runoff strips gave higher RR ratio values of 0.25 and 0.20 for stones and about the same values of 0.06 and 0.04 for organic reed mulches compared to full maize stalk mulch cover of this experiment (RR ratio ≈ 0.053).

From this discussion, therefore, it can be concluded that, the runoff channelled to the basins was greater from higher clay content soils and runoff producing strips with steeper slopes. Nevertheless, the top fine sandy textured layer and gentle slope of this experimental site caused higher infiltration on the runoff strips and relatively lower run-on into the basins compared to clay soils. However, the main focus is the partitioning of rainwater fallen into basins and runoff strips and it is of paramount importance in understanding the infiltration ratio of basin to runoff area (I_{BA}:I_{RA}) and the fraction of available water to the plant roots in the technique of IRWH.

4.3.3 Infiltration ratio of basin to runoff area (I_{BA}:I_{RA})

The combined effect of various mulch levels and runoff strip lengths on calculated infiltration ratios (I_{BA}:I_{RA}) for basin to runoff area are presented in Table 4.4. The statistical analysis of variance indicates that the interaction effect of surface treatments (RSL and ML) on the I_{BA}:I_{RA} showed highly significant differences (P < 0.0001) with LSD value of 0.039.

Table 4.4 Analysis of variance of the effect of mulch cover levels and runoff strip lengths on estimated infiltration ratios (I_{BA}: I_{RA}) of runoff to basin area.

Runoff strip length (RSL)	Mulch level (ML%)				
	0%	12%	39%	64%	96%
1 m	1.34d	1.30e	1.24f	1.19g	1.16gh
1.5 m	1.35d	1.32de	1.25f	1.21fg	1.16gh
2 m	1.50b	1.45c	1.35d	1.29e	1.22fg
3 m	1.62a	1.47cb	1.24f	1.12h	1.05i
LSD:	RSL × ML = 0.039				

means followed by the same letter are not significantly different (P< 0.0001)

From the results it is clear that the bare (ML0%) and low mulch cover (ML12%) in all RSL treatments gave higher infiltration ratios than those for high mulch covered RSL treatments. The infiltration ratio during the growing season for bare and low mulched plots varied in the range of 1.30 to 1.62. The higher infiltration ratios were observed on the wide RSL-3 ML0% and RSL-2 ML0% bare treatments than on narrow RSL-1 and 1.5 bare treatments. However, the bare RSL-3 ML0% had significantly higher values by about 7.5% compared to bare RSL-2 ML0%, while the low mulch cover did not show significant differences between RSL of 3 m and 2 m. In the case of ML39% cover, all the RSL treatments with the exception of RSL-2 gave nearly similar I_{BA}:I_{RA} values. The higher mulches cover (ML64% and ML96%) showed considerably lower I_{BA}: I_{RA} values, although the full mulch cover (ML96%) showed lower I_{BA}: I_{RA} values than ML64% cover. Nevertheless, the RSL-2 remained with significant higher infiltration ratio for both ML39% and ML96% treatments compared to other respective RSL treatments. Therefore from I_{BA}:I_{RA} estimations, it can be indicated that: (i) With an increase in mulch cover level, the fraction of infiltrated water in the basin area reached a higher value only on two meter long runoff (RSL-2 treatments). This implies that high runoff occurred from where there is insufficient mulch cover in the runoff section, and a high infiltration will occur for bare and maximum of two meter long runoff length. (ii) RSL-3 treatments with minimum mulch cover (ML0% and ML12%) observed higher infiltration and showed much lower value with an increase of mulch rate application. (iii) The RSL-1 and RSL-1.5 treatments however, have shown insignificant differences between different mulch cover treatments nonetheless, both RSL-1 and 2 gave higher I_{BA}: I_{RA} than RSL-3 treatment when the mulch cover level increases.

Therefore, management of the soil surface can significantly affect runoff, and infiltration, in particular, for the wide (RSL-3) treatments, the amount of runoff and infiltration was highly influenced by the mulch cover compared to narrower RSL treatments. This leads one to select an appropriate interaction of the surface treatments for better cultural management in the technique of IRWH. However, in general the most important parameters are what fraction of rainwater infiltrated into the basin, to be easily accessed by the plant roots, and the rainwater conserved in the runoff strip profile that will be used by the plants during a dry spell. Thus, the reduction of soil water evaporation from both basins and runoff strips is of paramount importance for efficient rainwater use for growth and productivity in the semi-arid climatic conditions. This will be discussed thoroughly in Chapter 5 and 6 of this study.

4.4 Conclusion

The purpose of the present study was to ascertain the effectiveness of surface treatments to quantify the partitioning of rainwater falling on the runoff strips and basins as well as to determine the fraction of rainwater available to infiltrate into the root zone for crop growth and productivity.

In the basin (planting zone) the canopy rainfall interception is a distinct process that needs to be consider in the technique of IRWH. The estimation of RCI revealed that the highest interception was in the range of 4.5% to 9.0% of the precipitation for various RSL treatments. However, small rains and during the initial growth stage the RCI was insignificant. In general, the RCI capacity of a maize field under IRWH reached plateau at about 0.5 – 0.6 mm for narrow RSL and 1.0 – 1.1 mm for wide but the RCI efficiency depends on the rainfall characteristics and surface treatments (particularly the length of the runoff strips) and the frequency of rain events during the growing season. This indicates that on the wide treatments, the RCI losses that would be evaporated from the canopy were higher than those from the narrow RSL treatments.

From the mean results of runoff-rainfall (RR) ratios, the lowest efficiency was observed from fully mulched wide RSL treatments i.e. only about 4% of the rainfall, while the highest mean RR was about 27% from bare narrow RSL-1 treatments. The medium efficiencies (about 10 - 11%) were observed on the mulched RSL-1.5 and RSL-2 treatments. This variation in RR clearly indicates that the partitioning of rain falling into basins and onto runoff strips depends on the surface treatments. The rainwater running into the basin could be used directly by the plants whereas the water that was infiltrated into the root zone of the runoff strips becomes available for crop transpiration during dry spells. These results were confirmed from established relationships of ML – RR and RSL – RR on the account of induced infiltration by the mulch cover and physical properties of the soil, respectively. From the relationship of infiltration ratio with surface treatments it can be concluded that the I_{BA}:I_{RA} into the basin area of RSL-2, with an increasing mulch cover, was much higher compared to other treatments. However, the wide RSL-3 treatment showed higher I_{BA}:I_{RA} on bare plots but declined with an increase in mulch cover. With increasing mulch cover, the I_{BA}:I_{RA} values of narrow RSl-1 and RSL-1.5 were between the RSl-2 and RSL-3 treatments. Therefore, these variations in fractions of rainwater that can infiltrate into basins and runoff areas can lead one to select alternative strategies and improve water harvesting techniques.

CHAPTER 5

Quantifying and Predicting Soil Water Evaporation as Influenced by Runoff Strip Lengths and Mulch Cover

5.1 Introduction

Direct evaporation of water from the soil surface is a wasteful loss of potentially productive rainwater. More efficient use of rainwater in areas with limited precipitation can help to sustain agricultural production in these semi-arid areas. In dryland environments, soil evaporation accounts for 30 – 50% of rainfall (Cooper *et al.,* 1987; Wallace, 1991), a value that can exceed 50% in sparsely cropped farming systems in semi-arid regions (Allen, 1990). Thus a considerable proportion of the rainwater that could be used for growth and development is lost. This unproductive loss of rainwater can be reduced by a variety of management practices (Gill and Jalota, 1996) of which mulching practices (Hensley *et al.,* 2000; Botha *et al.,* 2003) and optimum runoff to basin area ratio are most feasible to enhance rainwater harvesting into the root zone (van Rensburg, 2010).

From a practical approach, Stroosnijder (1987) described how soil water evaporates from bare soils at a potential rate only for one or a few days after rainfall (first stage). Thereafter, soil evaporation, Es is reduced due to drying of the soil surface (second stage). It is assumed that the two soil evaporation stages are distinct and only the first stage is driven by potential evaporation in semi-arid conditions. This means reducing Es depends on the stage of the process: whether it is during first stage, in which meteorological factors acting on the soil surface dominate the process, or the second stage determined predominantly by the physical properties of the soil profile (Hillel, 2004).

A number of models have been proposed and developed to estimate evaporation from soils beneath the crop, for example Ritchie (1972), Shuttleworth and Wallace (1985) and Boesten and Stroosnijder (1986). However, their application is limited. Several mechanistic models have also been reported in the literature to estimate Es using the general flow of water (Rose, 1968; Gardner and Gardner, 1969; van Bavel and Hillel, 1976). Ritchie (1972) developed a simple functional model to estimate daily Es under second stage evaporation, based on the diffusivity theory. This model has been widely used to estimate Es because of its validity and simplicity (examples - Shouse *et al.,* 1982; Jury *et al.,* 1991; Yunusa *et al.,* 1994; Botha, 2006; Nhlabathi, 2010). Ritchie's model assumes a linear relationship with a zero intercept between cumulative soil evaporation (∑Es) and the square root of time ($t^{1/2}$). The value of the slope (α') characterizes the evaporation process (mm $d^{0.5}$) and t is time (days) after rainfall:

$$\sum Es = \alpha'(t)^{1/2} \quad \textbf{5.1}$$

Ritchie's model in Eq. 5.1 does not account for the first stage of soil water evaporation and Ritchie (1972) modified it by considering both stage-1 and stage-2.

In this model Stroosnijder and Kone (1982) assumed that the first stage of Es is equivalent to potential evaporation. Boesten and Stroosnijder (1986) proposed a simple parametric model to estimate daily evaporation by using cumulative actual evaporation during a drying cycle as being directly proportional to the square root of potential evaporation. Instead of taking time as an independent variable, Boesten and Stroosnijder (1986) developed a parametric model by which Es is computed from the meteorological data only. Boesten and Stroosnijder (1986) used potential evaporation in a practical way to calculate actual Es for both evaporation stages, proceeding as follows:

$$\sum Es_1 = \sum E_{pot} \quad \text{for } \sum E_{pot} < \beta'^2 \text{ or } \sum E_{pot} = \sum Es_1 = \beta'^2 \quad \text{(Stage-1)} \quad \textbf{5.2}$$

$$\sum Es_2 = \beta'(\sum E_{pot})^{0.5} \quad \text{for } \sum E_{pot} \geq \beta'^2 \quad \text{(Stage-2)} \quad \textbf{5.3}$$

where ∑Es (mm) is the sum of actual measured soil water evaporation per day, E_{pot} is potential evaporation rate in mm d^{-1}; the summation (∑) in mm is the cumulative amount over the drying period and β' is the evaporation physical parameter of the soil ($mm^{0.5}$) determined experimentally as slope of graph ∑Es versus $\sum E_{pot}^{0.5}$.

For this model ∑Es depends on cumulative $\sum E_{pot}$ not on time. The β' ($mm^{0.5}$) value is an evaporation parameter characteristic of the soil to be determined experimentally. This implies that Es of each day is directly proportional to the atmospheric evaporative demand of that day which can have large daily variation (E_{pot}) during the drying cycle. Moreover, it makes the value of β' less dependent on E_{pot} than α' is dependent on time, according to Boesten and Stroosnijder (1986). Accurate estimation and modelling of Es are needed, so as to compare management strategies that minimize water losses and can help to determine management strategies that conserve water in dryland crop production. Moreover, it is of prime concern to reduce Es losses in order to increase the storage of plant available water in the root zone and therefore cause a greater fraction of evapotranspiration (ET) to be used as transpiration from cropped fields.

The use of 1:2 m basin to runoff strip length in IRWH has been accepted as standard practice for all ecotopes. This recommendation was made on tacit knowledge for row width and originated from conventional tillage practices. It was not a major issue at that time because the main aim was to introduce the new technique to farmers east of Bloemfontein, where it was developed. Today, IRWH is applied across three provinces (Free State, Eastern Cape and Limpopo) in South Africa with widely differing climate and soil conditions across those production areas. Thus, the research question was posed whether the 1:2 m basin to runoff strip length really represents optimum water harvesting conditions for crop production in all areas. This research question will be fully addressed by the water balance calculations in Chapter 7. However, in order to understand the effect of different runoff strip lengths, it is important to quantify and evaluate how the soil water evaporates within different basin to runoff strip lengths.

Another cultural practice of huge importance to restrict Es in IRWH, is mulching. This topic was introduced by Hensley *et al.* (2000), as a means to restrict the high Es losses that occurred under dryland cultural practices in semi-arid zones. In addition, all the research on the effect of mulching on Es was conducted on the standard IRWH (1:2 m) basin to runoff strip length. Nevertheless, it is crucial to understand how Es is affected by mulches for the broader application of IRWH with different runoff strip lengths. Furthermore, quantifying the soil water evaporation rate from a crop field with a non-homogenous nature of basin areas and runoff sections within the technique of IRWH is not an easy task, especially over long periods. Empirical models of Es can help to understand how the soil surface evaporation from the different sections of the IRWH is affected. The hypothesis of this chapter is therefore, that the surface treatments of runoff strip length (RSL), and mulch level (ML) will affect the Es beneath the maize crop produced under IRWH through the growing season. Hence, the purposes of this study were:

- to quantify the effect of surface treatments (RSL and ML) on soil water evaporation;
- to conduct a detail analysis of Es from each 1 m section of IRWH to quantify the effect of crop shading and mulch levels; and

- to evaluate the Ritchie and Stroosnijder Es models across the basin and runoff sections of IRWH.

5.2 Materials and methods

5.2.1 Experimental design and layout of microlysimeters

With the aim to evaluate the surface treatments (RSL, ML and canopy shading, CS), field trials were carried out on a maize crop under the technique of IRWH for two consecutive seasons (2007/08 and 2008/09). The mulch application was only implemented for the second season, as the first season was used to set-up the basins and runoff strips. The main experimental design and treatments were described in Chapter 2 Section 2.3.1. Accordingly, there were four runoff strip lengths (RSL) and five mulch levels (ML) each replicated three times. The RSL treatments comprised of 1, 1.5, 2 and 3 m runoff strip lengths and the MLs were expressed as percentage of surface covered by mulch *viz.* 0% (bare), 12%, 39%, 64% and 96%.

For this experiment, all the RSL treatments (1, 1.5, 2 and 3 m) and three of the ML treatments (bare 0%, 39% and 96%), were used to measure Es. There were also four different canopy shading (CS) treatments, *viz.* a full shade basin area (FC-BA), a full shade runoff area (FC-RA), a partial shade runoff area (PC-RA) and an unshaded runoff area (UC-RA). Due to the magnitude of the experiment, only one replicate was employed, but measurements were done for three consecutive drying cycles (DC). The DC periods were each 7 days; as follows: 15-21 March (84-90 DAP), 4-10 April (104-110 DAP) and 8-14 May (138-144 DAP) in 2008/09 season.

Soil water evaporation measurements were carried out using microlysimeters (MLy). The mode of construction, installation and handling of the microlysimeters at the field level were described in detail in Chapter 2, Section 2.4.2.3. The layout of the microlysimeter sites was made according Fig. 5.1 to represent both basin area (BA) and each one meter section of the runoff area (RA). Thus, the number of MLys installed was determined by the length of the runoff strip section; one MLy in RSL-1 (named RA1) and two MLys in RSL-2 (named RA1 and RA2) and in RSL-3 three MLys (named RA1, RA2 and RA3) as shown in Fig. 5.1. These were used to separate the effect of canopy shading (CS), *viz.* full shaded (FC) section, partial shaded (PC) section and the unshaded (UC) section. The water loss through Es was weighted according to the relative contribution of each section within the system of IRWH plot.

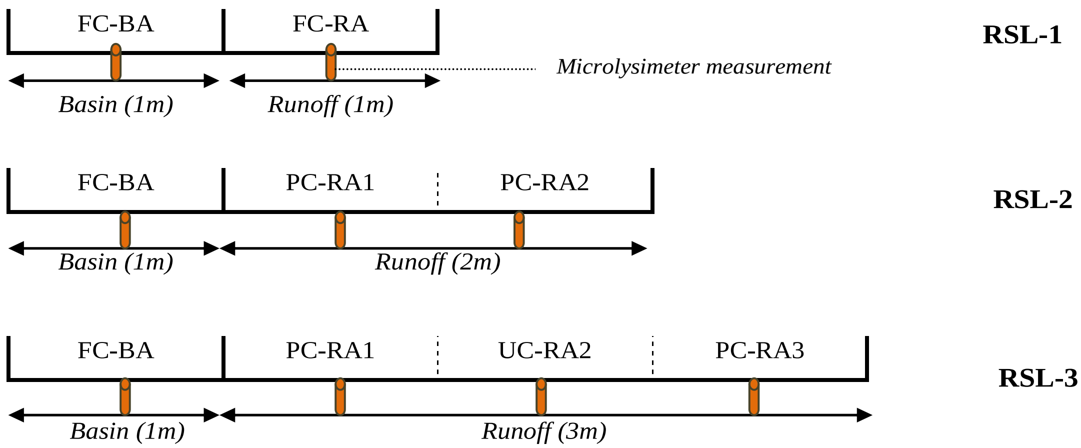


Figure 5.1 Schematic diagrams showing the cross section of the IRWH system with basin area (BA) and runoff area (RA) with shading spatial attributes and position of microlysimeters on the 1 m runoff strip length (RSL-1), 2 m runoff strip length (RSL-2) and 3 m runoff strip length (RSL-3) treatments. FC-BA= full canopy shading in a basin, FC-RA= full canopy shading in runoff, PC-RA= partial canopy in the runoff and UC-RA unshaded area in the runoff.

FC-BA represents the basin area of all RSL treatments, where the 1 m wide maize rows were growing and FC is also represented by the narrow runoff (RSL-1) areas where the area is shaded from both sides by adjacent rows. In contrast, on wide 3 m runoff strips the two sides of the runoff strips were partially shaded (RA1 and RA3) from either side by the crop rows, so this partially shaded section of the runoff is abbreviated as PC (Fig. 5.1). However, the centre, at RA2 (RSL-3) where neither side crop rows can shade this middle section of the runoff at midday, represents an unshaded (UC) area (Fig. 5.1). The RSL-2 also comprises two sides with partially shaded sections (RA1 & RA2). Similar arrangement of BA and RA were also performed for the RSL-1.5 with full shading in both the basin and runoff strips.

5.2.2 Empirical relationships and model development

During the cropping season 2008/09, cumulative Es measurements were used to evaluate empirical equations related to time and potential evaporation. Both the Ritchie (1972) model and the Boesten and Stroosnijder (1986) model were used as a base for the construction of the estimation equations for Es under a IRWH maize crop. Hence, measured cumulative evaporation from the soil and cumulative potential evaporation during a drying cycle were used to obtain β' value (soil physical parameter) from slope of ∑Es versus $(\sum E_{pot})^{0.5}$ for the bare soil (Boesten and Stroosnijder, 1986). Daily estimations of potential evaporation (E_{pot}) were calculated from the reference evapotranspiration, ETo which was obtained by using FAO-56 Penman Monteith equation (ETo) (Allen *et al.*, 1998) with meteorological data measured at the automatic weather station within the experimental plot.

For the purpose of the study, the E_{pot} in the maize field was obtained with a conversion factor (crop coefficient, *Kc*) value of 1.1 of the reference evaporation (E_{pot} = 1.1ETo). In these circumstances evaporation proceeds at the rate determined by atmospheric demand for water vapour, so that evaporation rate is maximum and E_{pot} is considered to be greater than ETo (Azam-Ali and Squire, 2002). According to Loomis and Conner (1992) the value of E_{pot} varies among different crops owing to differences in colour, height, aerodynamic characteristics and stomatal control.

5.2.3 Model determination and evaluation

The evaporative parameters of the soil (α' and β') were determined for bare and mulched soil surfaces under a maize canopy, during three consecutive drying cycles. The main criterion, that each period was proceeded by rain recharged of at least the top 300 mm of the soil profile and followed by dry days (rain free) for a period of about 7 days. The empirical models were tested under a range of ETo regimes, as reflected by the three drying cycles. The two empirical models for Es were also compared by considering the effects of shading and mulch across both basin and runoff areas on soil parameters α' and β'.

The performance of the models depends on how well predicted ∑Es values for each shading level (full and partial canopy and unshaded) from both Ritchie and Stroosnijder models agreed with measured values. For the purpose of calibration of the models, the observed soil evaporation data set of DC-1 and DC-3 were used; and for the verification purposes the DC-2 data set were applied, as independent field data of Es were not available.

5.2.4 Statistical design analysis

The statistical variation of the weather conditions during the drying cycles were analyzed only by using the mean and standard deviation values. Total soil water evaporation data collected during the drying cycles were statistically analyzed using the statistical software SAS 9.1.3 for Windows

(SAS Inst. Inc., 2006). Primarily, the three drying cycles were computed, and tested to see if there was a statistical difference between the drying cycles. Secondly, for the main effects of RSL and ML treatments, statistical analysis was performed on the weighted Es values in the system of IRWH. Thirdly, for each 1 m section of the IRWH system, the two treatment effects of ML and CS were considered for their effective contribution to Es reduction during a drying period. Fourthly, the study also presents a statistical analysis for the model results of α’ and β’ values.

Thus, for the first two statistical design analyses, a non-replicated two way factor interaction in a split plot arrangement was adopted in order to analyze the effect of the treatments for each drying cycle as described by Sokal and Rohlf (1981) and Box and Jones (1992). In contrast, the other two statistical analyses had unequal replications due to the nature of the experiment. For the data not meeting the required number for equal or proportional replication, the mean values were inserted as an additional data point, as follows (Shearer, 1973; Zar, 1994). In this case, the analysis proceeds with total degrees of freedom (DF) and a factorial analysis of variance were performed after inserting the mean to equalize the disproportional replications. The Least Significant Difference (LSD) test was used to separate the statistically significant means. For the values of α’ and β’, a comparison of the means was made only for two drying cycles (DC-1 and DC-3). Thus, means and LSD values for the main treatment effects were computed for DC-1 and DC-3. For the models application, the measured and estimated Es values were compared using simple regression procedures and mean statistics were given by Willmott (1981; 1982).

5.3 Results and discussion

5.3.1 Weather condition during drying cycles

The weather conditions as reflected by temperature and ETo during the three drying cycles are summarized in Table 5.1. All the DCs fall into the autumn season: DC-1 in March, DC-2 in April and DC-3 in May 2009. The weather conditions during the first two DCs are almost similar; the mean temperature differs by less than 1^{o}C and the mean ETo by 0.6 mm d^{-1}. The third DC, however, is cooler with lower evaporative demand conditions than the other two cycles. This was expected because of the temperature and ETo decline sharply during May as part of natural seasonal change towards winter (Zerizghy *et al.*, 2011). The total ETo during DC-1 (27.5 mm) was generally greater and more variable than during DC-2 and 3, though the temperature was lower during the first DC compared to second DC. The growth stages during drying cycles are also given in Table 5.1. Accordingly, the first two DCs fall into the reproductive stage (GS-III) and the third DC in physiological mature stage (GS-IV). Consequently, the variation between DCs and within a drying period (days) shows that the actual Es measurements were induced by the prevailing weather conditions.

Table 5.1 Mean daily air temperature and reference evapotranspiration during three drying cycle periods, *viz*. first: 15-21 March, second: 4-10 April and third: 8-14 May, 2009.

Drying cycle (DC)	**DC-1**		**DC-2**		**DC-3**	
Growth stage (GS)	**GS-III (84-94 DAP)**		**GS-III (104-110 DAP)**		**GS-IV (138-144 DAP)**	
Drying period (day)	Temp. (^oC)	ETo (mm d^{-1})	Temp. (^oC)	ETo (mm d^{-1})	Temp. (^oC)	ETo (mm d^{-1})
1	19.8	3.5	19.5	3.2	13.0	2.3
2	20.3	3.8	20.3	3.2	12.2	2.2
3	19.9	4.6	20.1	3.4	12.6	2.2
4	16.7	4.2	20.2	3.3	13.1	2.6
5	17.3	2.8	18.5	3.0	13.1	2.6
6	17.9	4.3	18.9	3.4	14.0	2.8
7	18.3	4.3	20.2	3.7	14.6	2.5
Total		27.5		23.2		17.2
Mean	18.6	3.9	19.7	3.3	13.2	2.4
Std. dev.	1.4	0.6	0.7	0.2	0.8	0.2

5.3.2 Effect of runoff strip length and mulch level on Es

The change in atmospheric conditions and the ability of the surface to conduct heat determines the amount of evaporation lost from the soil surface. The statistical comparison of the total Es measured between different DCs showed that there was a highly significant difference present at $P < 0.0001$ level (Table 5.2). The highest total amount of Es was observed during the second drying cycle (12.6 mm), being nearly double the amount of the third drying cycle. Consequently, DC-3 obtained the lowest total Es and ETo values. This was probably induced by the lower daily air temperature and atmospheric evaporative demand of DC-3 compared to the other DCs (Table 5.1). However, the main concern was the reverse affect on atmospheric evaporative conditions of DC-1 and DC-2 relative to the measured total Es values. Thus, in DC-1, when the ETo was higher, the total Es showed a lower value than DC-2; and the opposite occurred when ETo was lower in DC-2. The main reason for higher total Es in DC-2 could be associated with higher temperatures and thus a soil surface heat conductivity (not measured) effect, in particular during the energy limited stage of evaporation. In contrast, the lower total Es, but higher ETo in DC-1 with relatively lower temperature indicates a dependence, to a large extent, on the energy supply as radiant energy and air movement by prevailing winds are the main driving forces for evaporation. As a result, the surface treatments can play a significant role in reducing soil water evaporation losses under crop field conditions.

Table 5.2 Effect of runoff strip length (RSL) and mulch level (ML) on total soil evaporation during the drying cycles (DC).

Variable	Total Es during drying cycles (mm)		
	DC-1	**DC-2**	**DC-3**
A) Runoff strip length (RSL)			
RSL-1	9.1	13.2	7.0
RSl-1.5	8.5	12.2	7.2
RSL-2	8.4	12.1	6.5
RSL-3	8.6	12.8	6.4
B) Mulch level (ML)			
ML0%	9.5a	14.4a	7.5a
ML39%	8.4b	11.7b	6.5b
ML96%	8.1b	11.6b	6.4b
Mean (DC)	**8.6b**	**12.6a**	**6.7c**
LSD: **DC = 0.55**	**RSL = ns**	**ML = 0.56**	**RSL×ML = ns**

** indicate significant differences at 5% probability levels and ns is non-significant.*

Surface treatments are known to change the evaporation rate by operating lower than the potential evaporation rate. The statistical results for total Es showed no significant difference for the combined surface treatments (RSL and ML) during each drying cycle (Table 5.2). This clearly indicates that with the addition of mulch on extended runoff strips, did not systematically influence the total Es values. Therefore, it is an important step to assess the surface treatments separately for the effect on total Es losses during each drying cycle. Thus, among the two surface treatments, the results showed that the ML had a significant effect on Es during each drying cycle with LSD value of 0.56 (Table 5.2). Across all three drying cycles, the highest Es was observed from the bare (ML0%) treatments. However, the total Es from the two mulched treatments *viz.* ML39% and ML96% was not significant different. Thus, it is clear that mulch reduced soil water evaporation across both stages of evaporation, and was influenced by a lower energy supply level at the site of evaporation. This lower Es was probably due to the mulches' greater reflection resulting in less absorption of solar radiation and lower thermal conductivity than the bare soil (van Doren and Allmaras, 1978: Jalota and Prihar, 1998).

The magnitude of Es reduction from different levels of mulch depends on the evaporation processes. More interestingly, in all DCs, the application of lower levels of mulch (39%) is nearly as efficient as higher mulch levels (96%) in reducing evaporation. In this case, the soil physical properties at the experimental site play a great role in enhancing infiltration capacity because of lower total loss of water underneath the mulched runoff strips. In the initial stage, Es from the fully mulched runoff strips lags behind and was slower in drying compared to lower mulched or untreated bare soils, but after some time (Stage-2) a dry layer develops in bare and lower mulched plots, thereafter the difference between total Es for lower and higher mulched strips under IRWH becomes very small. This is due to the unsaturated hydraulic conductivity of the fine sandy soils that decreased drastically and the rate of evaporation falls sharply (Gill and Jalota, 1996). As a result, the rate of evaporation from fully mulched soils begins to exceed that of a lower mulch treated surface of the runoff area. For example, for the IRWH study during summer time Botha (2006) found a total Es of 127 and 134 mm over 71 days, which is equivalent to 12.5 and 13.2 mm per 7 days for 100% and 50% organic mulch cover, respectively. These results were lower by 2.3 and 3.3 mm compared to bare treatments while the two mulch levels did not shown a significant variation. This is in good agreement with these experimental results on total Es with only on average of 0.2 mm difference over all three drying cycles. Botha *et al.* (2003) suggested that mulched surfaces could give crop roots time to extract a greater portion from the surface compared to bare plots. Thus, the presence of mulch in the runoff strips reduced the effectiveness of liquid flow from the cross-sectional runoff area and that change caused the rate of evaporation to decline compared to the bare runoff strips

In contrast to the effect of ML, there was no effect of RSL detected in any of drying cycles (Table 5.2). The highest total Es was observed from the narrow RSL treatments. The wide RSL-3 and RSL-2 reduced evaporation by about 7-8% and 3-9%, respectively, but in general all three DCs did not show a consistent trend of decreasing Es losses with an increase in length of runoff strips. Thus, from this analysis, the insignificant effect of RSL treatments on Es implies that, the dynamics of spatial distribution of soil water and energy that influence evaporation were probably obscured by averaging Es values over the IRWH tillage system. This meant that, each 1 m parcel of the IRWH system contributes a different Es through the effect of green or dry mulch cover in a different manner, and the effect is lost when combined as a mean. Hence, the various positions of

IRWH should be expressed according to the effect of “green mulch” or shading cover (CS) on Es beneath the maize canopy as will be discussed in the next section.

5.3.3 Effect of mulch level and canopy shading on Es

From the analysis, the various positions within the system of IRWH have to be considered in order to evaluate the surface treatments effectively. The comparison comprises the effect of shading and mulch cover simultaneously, these are: a) full canopy shading basin area, FC-BA; b) full canopy shading runoff area, FC-RA; c) partial canopy shading runoff area, PC-RA; and d) the unshaded runoff area, UC-RA as described in Fig. 5.1. Thus closer examination may reveal the more dynamic nature of Es beneath the maize canopy under IRWH techniques.

The absence of significant interaction between RSL and ML allowed one to consider different positions in the system of IRWH with total Es values for each 1 m across the basin and runoff section areas. Consequently, mulch levels by various positions (canopy shade effect) interactions were detected for each drying cycle (Table 5.3). Thus, the statistical comparison of total Es revealed that in the tillage system of IRWH, the combined treatments (ML and CS) influenced the total Es for each drying cycle, with LSD value of 0.34, 0.39 and 0.31 for DC-1, DC-2 and DC-3, respectively (Table 5.3). Only the combination treatments that affected Es significantly will be further discusses. Accordingly, the treatment combinations as indicated in Table 5.2 were grouped into three Es classes depending on the ability to restrict Es losses for each drying cycle. Thereby, the three classes were marked as: the class that performed the poorest were the treatments that had Es values above 8.7, 13.3 and 6.9 mm for the DC-1, 2 and 3, respectively; the intermediate class Es values fell between 8.5 - 8.7 mm, 12.0 - 12.9 and 6.5 - 6.7 mm; and the most efficient class had Es values below 8.4, 12.2 and 6.4 mm, respectively.

Class with poor Es restrictive properties:

In all the DCs the highest total Es was observed in the bare treatments (ML0%) with all variety of CS patterns (FC-BA, FC-RA, PC-RA and UC-RA).The magnitude of Es varied between the DCs *viz.* 8.7 – 9.4 mm in DC-1, 13.4 – 14.3 mm in DC-2 and 6.7 – 7.4 mm in DC-3. Nevertheless, on both mulched plots of ML39% and ML96% cover with the FC-BA (8.8 & 8.6 mm) and FC-RA (6.9 mm) treatments during DC-1 and DC-3, gave relatively higher total Es values nearly at the bottom range of this group. The basin area of all the different runoff strip lengths (RSL-1, 1.5, 2 & 3) are all the same size with no mulch at all. Therefore, one might expect that the Es from these would be similar, as long as the soil surface had relatively the same water contents. This can easily be true soon after rainfall and when collecting run-on in the basins being maintained quite wet after a rain storm. With less restricted upward flow of water from bare soils a dry surface develops more rapidly than on the mulched plots.

Table 5.3 Statistical analysis for the effect of runoff strip length (RSL), mulch level (ML), and canopy shading (CS) on total soil evaporation during each the drying cycles (DC)

Interaction (ML*CS)		**Total Es during drying cycles (mm)**		
ML	**CS**	**DC-1**	**DC-2**	**DC-3**
0%	FC-BA	9.4a	13.4b	7.1ab
	FC-RA	9.0bc	13.6b	7.4a
	PC-RA	8.7de	13.4b	6.9bc
	UC-RA	9.1ab	14.3a	7.2ab
39%	FC-BA (bare)	8.8bcd	12.0d	6.6cde
	FC-RA	8.4fgh	12.2d	6.9bc
	PC-RA	8.2hi	12.1d	6.4e
	UC-RA	8.6def	12.9c	6.7cde
96%	FC-BA (bare)	8.6def	11.9d	6.6cde
	FC-RA	8.3ghi	12.2d	6.9bc
	PC-RA	8.1i	12.0d	6.4e
	UC-RA	8.5efgh	12.9c	6.6cde
ML×CS	***(LSD)***	**0.34**	**0.39**	**0.31**

**indicate significant differences at 5% probability levels and ns is the non significant level.*

Low class total Es values (High Es restrictive properties):

In this study, the partial canopy cover position was revealed in the low class of total Es values. Thus, the low class group include all the mulched plots under the partial canopy shade cover (ML39% PC-RA and ML96% PC-RA) in each DC-1, 2 and 3 with total Es values of 8.1 – 8.4 mm, 11.9 – 12.2 mm and 6.4 mm, respectively. Evidently, some of the full cover basin and runoff area also showed total Es values in this class range. For instance, the total Es value for DC-1 and 2 from the mulched plots with full canopy cover in the runoff strip (ML39% FC-RA and ML96% FC-RA) were at the top of the range i.e. 8.4 and 12.2 mm, respectively. As the microlysimters were positioned across the length of the runoff section in wide strips, these Es measurements under mulch cover surface show the spatial effect of shading from the crop canopy as “green mulch” and effect of the “dry mulch”, simultaneously. With this high Es restrictive class, the soil surface under higher mulch and shading cover remains wetter than the bare surface but is mainly caused by high infiltration capacity of the soil of the experimental site.

Intermediate class with restrictive properties:

In the case of the mulched plot with no shade in the mid section of RSL-3 (ML39% UC-RA and ML96% UC-RA) intermediate total Es values were obtained of about 8.6, 12.9 and 6.7 mm for DC-1, 2 and 3 respectively. Similarly, in DC-3, the mulched plots with full canopy cover in the basin area (ML39% FC-BA and ML96% FC-BA) rendered the same total Es values. However, closer examination of the data revealed that the higher total Es from bare and full canopy shade (FC) were lower from full mulched and partial shade (PC) showing the major contribution for the interaction effect. During the drying cycles, the reduction of Es due to both combined effects of mulch and shading between poorly and efficiently restrictive losses of the treatments were found in the range of 0.3 - 1.0 mm, 1.4 - 2.1 mm and 0.5 - 1.0 mm for DC-1, 2 and 3 respectively. These values correspond to daily average Es reduction losses of 0.04 - 0.14 mm d^{-1}, 0.20 - 0.30 mm d^{-1} and 0.07 - 0.14 mm d^{-1}, respectively between the poorly and efficiently restrictive losses.

In general, the average reduction of Es rate from the combined effect of ML and CS was about 2.7, 1.5 and 1.4 mm d^{-1} for DC-1, 2 and 3, respectively. These values are in agreement with the finding of other authors (Todd *et al.*, 1991; Adams *et al.*, 1976), but suggested that effects of mulch and crop canopy shade are independent of each other under dryland production without water harvesting and under limited irrigation. Shading by maize canopy under dryland condition significantly reduced the Es by 0.5 and 0.3 mm d^{-1} and under limited irrigation by 0.6 and 0.7 mm d^{-1} for two consecutive seasons (Todd *et al.*, 1991). However, mulch cover reduced Es by less bening an average of 0.1 and 0.5 mm d^{-1} for both years under dryland and limited irrigation. Similarly Adams *et al.* (1976) described the contribution of sorghum canopy shade and mulch to the total reduction of evaporation. Thus, the shade effect accounted for about three-quarters and the mulch effect accounted only for about one-quarter of the reduction under dryland conditions similar to the results of Todd *et al*. (1991). Under limited irrigation, the shading and mulch contributed about equal to the reduction of evaporation. However, from the result of this experiment with IRWH, it is clear that the mulch and shade acted dependently based on the data of both stage-1 and 2 of evaporation. Considering this, the main effect of shading on bare and unshaded treatments was due to the dominant effect of energy limited evaporation (Stage-1), while the mulched treatments were mainly driven by soil limited stage (stage-2) of evaporation. Therefore, it is inferred that cumulative Es for both stages of evaporation are rational in evaluating evaporation loss using empirical models applied to the technique of IRWH.

5.3.4 Evaluation of Ritchie and Stroosnijder models

5.3.4.1 Determination of α' and β' values

Different models were used to calculate soil evaporation by parameterzing wetness at the soil surface (α' method) or the soil water diffusion resistance (β' method). Table 5.4 presents both soil parameters in the calibration (α' and β') and summarize the statistical comparisons of main treatment (ML and CS) effects during both DC-1 and DC-3. The interaction effect of the treatments (ML and CS) was showed significant differences on both soil parameters α' and β'.

The α' values range from 2.96 to 4.26 mm $d^{-0.5}$ for DC-1 and from 2.34 to 3.26 mm $d^{-0.5}$ for DC-3, respectively. The bare plots during DC-1 exhibited the highest α' values for all CS treatments (4.02 to 4.26 mm $d^{-0.5}$), whereas both mulched plots gave the lowest values of α' for partially shaded and unshaded cover. For the DC-3, the higher α' value was found in a bare FC-RA, while both the mulched (ML39% and ML96%) PC-RA rendered lower α' values of 2.34 and 2.39. mm $d^{-0.5}$ Several researchers have attempted to quantify α' from the relation between cumulative Es and time. For example, Ritchie (1972) summarized the value of α' from different authors, using different soil types (van Bavel and Reginato, 1965; Black *et al.,* 1969: La Rue, *et al.*, 1968) with values in the range of 3.0 to 5.0 mm $d^{-0.5}$. In a field experiment on sandy and clay soils in West Africa Stroosnijder and Hoogmoed (1984) and Stroosnijder (2003) obtained a constant stage-1 drying time of 2 days and an α' value of 3.5 mm $d^{-0.5}$. However, much lower α' value of 3.00 and 3.11mm $d^{-0.5}$ were reported from the studies of the uncropped bare soils from the Glen/Bonheim ecotope with soils of 43% clay content and Glen/Swartland ecotope (38% clay content) in semi-arid area of the central part Free State of South Africa (Botha, 2006). Therefore, the results of α' value obtained from sandy loam soils of Kenilworth Bainsvlei ecotope highlighted the importance of the field data for Es beneath a maize canopy for different positions under IRWH.

Table 5.4 Statistical analysis on the calculated Ritchie α'(∑Es/(∑t)$^{0.5}$ and Stroosnijder β' ∑Es/(∑E_{pot})$^{0.5}$ values of bare, ML39% and ML96% treatments for different canopy shading pattern (FC-BA, FC-RA, PC-RA and UC-RA) during two drying cycles (DC-1 and DC-3).

Treatments		**Ritchie model (α') values** (mm $d^{-0.5}$)		**Stroosnijder model (β') values** (mm $d^{-0.5}$)	
ML	**CS**	**DC-1**	**DC-3**	**DC-1**	**DC-3**
ML0%	FC-BA	4.05a	2.92a-d	1.85ab	1.80abc
	FC-RA	4.24a	3.23a	2.06a	1.95a
	PC-RA	4.26a	3.03ab	1.98a	1.86ab
	UC-RA	4.02a	2.87a-d	1.91a	1.82abc
ML39%	FC-BA (bare)	3.90a	2.60c-f	1.81ab	1.64cde
	FC-RA	3.45bc	2.74b-e	1.81ab	1.67b-e
	PC-RA	3.04dc	2.34f	1.38d	1.50de
	UC-RA	3.48b	2.41ef	1.64bc	1.49e
Ml96%	FC-BA (bare)	3.98a	2.56def	1.87ab	1.58de
	FC-RA	3.11bcd	2.79bcd	1.47cd	1.69b-e
	PC-RA	3.25bcd	2.39ef	1.54cd	1.56de
	UC-RA	2.96d	2.94abc	1.40cd	1.71bcd
LSD:		***DC-1: ML×CS = 0.42***		***DC-1: ML×CS = 0.26***	
		DC-3: ML×CS = 0.38		***DC-3: ML×CS = 0.23***	

With regard to Stroosnijder model, the β' was computed lower compared to α' values, otherwise with treatment effect followed similar trend to the results of Ritchie model, where the highest β' value was obtained on bare plots during both DCs (Table 5.4). Similar to Ritchie model, the mulched cover plots were showed the lowest β' values. The β' values derived from the model were in the range of 1.38 mm $d^{-0.5}$ to 2.06 mm $d^{-0.5}$ and 1.49 mm $d^{-0.5}$ to 1.95 mm $d^{-0.5}$ for DC-1 and DC-3. Therefore, in general, it is clear that, there were variations of β' values during the DCs. This is probably due to different weather conditions in DC-1 and DC-3. The result of β' values found from different shading and mulch cover also showed similarities with the results obtained by Lascano and van Bavel, (1986) and Boesten and Stroosnijder (1986). For example, from microlysimeter measurements of soil evaporation, Boeston and Stroosnijder (1986) obtained a β' value of 1.7 mm $d^{-0.5}$ from an experiment conducted on loamy sandy soils in the temperate climates of Noordoost Polder in the Netherlands, which implies that total ∑Es measured was only 3 mm. Stroosnijder (1987) found similar results for a clay loam soil and therefore used a mean β' value of 1.65 mm $d^{-0.5}$ to calculate ∑Es. Hattingh (1993) reported a β' value of 1.60 mm $d^{-0.5}$ obtained from a fine sandy loam Hutton soil form at Glen in South Africa using measured Es from microlysimeters with depth of 150 mm. This result correlates well with those of Stroosnijder (1987).

In both cases, the relationships showed differences in the soil physical parameters. This is because of varying soil physical conditions. The degree of crusting and roughness caused by the sandy nature of the top soil and probably due to the effect of the surface treatments but assuming the soil properties could not differ significantly across all over the field. However, the models in this study, have introduced some variations in the estimating of ∑Es for homogeneous soils for different positions of the alternate arrangement of the IRWH under different field conditions. Thus, from this microlysimetric study of Es beneath the maize canopy, the obtained results for α' and β' are varied and the values found are within the range of different literature findings. However, the effect of canopy shading and mulch cover needs special attention to perform an evaluation and verification of the models.

5.3.4.2 Evaluation of the models

Verification of the models was performed with results obtained by using measured data from the DC-2. Cumulative Es were simulated in four canopy shade treatments (CS) under three mulch levels for both α' and β' models (Fig. 5.2). The performances of the models depend on how simulated ∑Es values for each canopy shade pattern under different mulch levels agree with measured values. Thus, the statistical values for the scatter plots indicate that both the models can estimate ∑Es from bare and mulched soil surface fairly well for the full and partially canopy shaded and for unshaded positions of the runoff strip (Table 5.5).

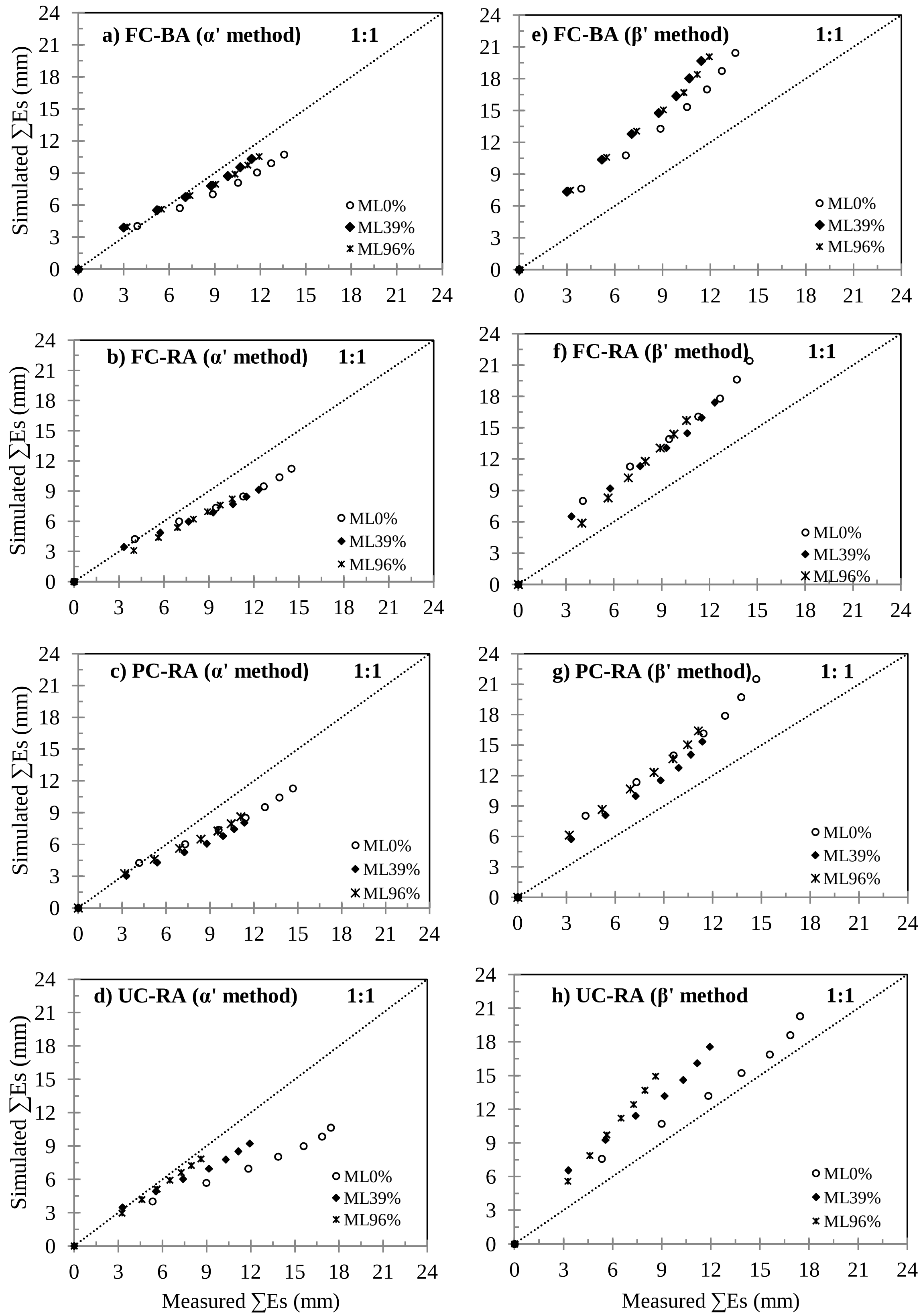


Figure 5.2 Measured versus simulated cumulative soil evaporation (∑Es) using α’ and β’ methods.

The magnitude of the prediction in these two models varied, as they is dependent on the time and atmospheric evaporative demand during the drying cycles. In all the treatments the simulated ∑Es were underestimated by the Ritchie model and in contrast overestimated by the Stroosnijder model. The slopes had values < 1 and >1 for α' and β' models, respectively, but the FC-RA and UC-RA under full mulch cover treatments gave same slope values of 0.781 and 0.911. The trends in both models, in general was reasonably well simulated relative to measured values. The linear regression fits were good in both cases with R^2 > 0.98. The D-index values (index of determination) for both variables are in a good agreement (Table 5.4). The RMSE and MAE were higher in β' model compared to α' model with values at the range of 5.92 – 1.02 mm & 5.44 – 0.92 mm and 2.44 – 0.54 mm & 2.04 – 0.49 mm, respectively, with the exception for the bare unshaded (UC-RA) treatments showed reverse values. Therefore, it can be seen that the two models showed variation on soil physical parameters with the effect of surface treatments (canopy shading and mulch cover).

Ritchie model

For Ritchie model, the RMSE were higher in the bare runoff areas for all canopy shade treatments compared to the mulched plots. The highest RMSE was observed in the unshaded runoff section (UC-RA), which is nearly double of the FC-RA and PC-RA. The unsystematic error (RMSEu) for the α' model of the basins (FC-BA) are not as high as RMSE (which is about 18%, 48% and 39% of the RMSE) and it is higher than the treatments for the runoff strips (FC-RA, PC-RA & UC-RA). This implies that the statistical tests for α' model provides relatively satisfactory results in the un-mulched basin area (FC-BA) compared to runoff strips with varying mulch and shading patterns with MAE values of 1.72, 0.73 and 0.83 mm.

Stroosnijder model

With respect to β' model the higher RMSE were exhibited for FC-BA treatments than the treatments located on the runoff strips (FC-RA, PC-RA and UC-RA). Moreover, the bare treatments FC-RA and PC-RA showed greater RMSE (4.82 mm and 4.77 mm) compared to mulched plots, however, the lower RMSE was found on the unshaded (UC-RA) bare and full mulched plots with RMSE values of 1.64 mm and 1.02 mm, respectively. Thus, the unsystematic errors ratio of RMSEu/RMSE is relatively better in a bare UC-RA treatment (36%) compared to bare FC-BA with only up to 13% unsystematic errors. Therefore, the MAE is much higher in the basin area (FC-BA) with values up to 5.87 mm and lowest MAE was found for unshaded bare and full mulch plots (UC-RA) with value of 1.58 mm and 0.924 mm.

Table 5.5 Statistical evaluation parameters for different cumulative soil water evaporation models on different canopy shading (CS) and mulch cover (ML) on Kenilworth Bainsvlei ecotope

a) Ritchie model (α')

CS	ML	RMSE	RMSEs	RMSEu	MAE	R^2	D	Slope (b)	$\frac{RMSEu}{RMSE}$
FC-BA (bare)	0%	2.046	2.019	0.330	1.718	0.990	1.000	0.745	0.176
	0%	0.841	0.735	0.409	0.730	0.983	1.000	0.839	0.486
	0%	0.998	0.917	0.392	0.837	0.985	1.000	0.824	0.393
FC-RA	0%	2.371	2.340	0.383	1.982	0.988	0.999	0.722	0.161
	39%	2.145	2.121	0.322	1.767	0.987	0.999	0.696	0.150
	96%	1.628	1.628	0.000	1.466	1.000	1.000	0.781	0.000
PC-RA	0%	2.440	2.414	0.354	2.047	0.990	0.999	0.724	0.145
	39%	2.321	2.306	0.259	1.950	0.989	0.999	0.666	0.112
	96%	1.699	1.676	0.279	1.387	0.989	0.999	0.730	0.164
UC-RA	0%	5.107	5.097	0.322	4.459	0.990	0.998	0.569	0.063
	39%	1.861	1.832	0.327	1.530	0.987	0.999	0.723	0.161
	96%	0.543	0.543	0.000	0.489	1.000	1.000	0.911	0.000

b) Stroosnijder model (β')

CS	ML	RMSE	RMSEs	RMSEu	MAE	R^2	D	Slope (b)	$\frac{RMSEu}{RMSE}$
FC-BA (bare)	0%	4.808	4.766	0.634	4.407	0.990	0.997	1.412	0.132
	0%	5.926	5.875	0.778	5.441	0.983	0.994	1.590	0.131
	0%	5.850	5.802	0.750	5.371	0.985	0.995	1.562	0.128
FC-RA	0%	4.827	4.771	0.734	4.437	0.987	0.998	1.369	0.152
	39%	3.728	3.677	0.614	3.447	0.987	0.998	1.319	0.165
	96%	3.081	3.081	0.000	2.773	1.000	1.000	0.781	0.000
PC-RA	0%	4.771	4.722	0.680	4.377	0.989	0.998	1.372	0.143
	39%	2.836	2.792	0.498	2.617	0.989	0.999	1.263	0.175
	96%	3.817	3.779	0.532	3.517	0.989	0.997	1.384	0.139
UC-RA	0%	1.761	1.643	0.635	1.581	0.990	1.000	1.078	0.361
	39%	4.064	4.015	0.625	3.747	0.986	0.997	1.371	0.154
	96%	1.027	1.027	0.000	0.924	1.000	1.000	0.911	0.000

**Data sets of 28 for FC-BA, 14 for FC-RA, 28 for PC-RA and 7 for UC-RA under different mulch cover*

From the statistical test, it can be generalized that: primarily, the relatively large RMSE and MAE values are due to the underestimation of the simulated ∑Es values for the α' model and overestimation of ∑Es for β' model. Secondly, the α' model seems more reasonably well performed in a bare basin area of the treatment (FC-BA), whereas the β' model relatively good in a bare unshaded runoff strips (UC-RA at ML0%). Thirdly, in both cases (α' and β') the full mulched plots (ML96%) in particular for treatments FC-RA and UC-RA, the unsystematic errors were shown to the highest, which indicates that the biasness of the mulch treatments on simulating ∑Es using the models.

In general, from the verification part, the Ritchie model performed better than Stroosnijder model, although the model results vary at different positions. Despite this Stroosnijder model will be used, as it gives a better RMSEu/RMSE over the wider range of treatments. However, the one calculated with potential evaporation renders better relationships to predict Es for canopy shade in a field with incomplete cover row crops (such as maize under IRWH). This demonstrates that the crop canopy shade pattern played a role in altering the atmospheric evaporative demand on field conditions. Therefore, when evaluating Es beneath a maize canopy, the consideration of weather parameters has an advantage, since the microclimate of the cropping system changes according to the basin and runoff arrangement practices. Consequently, it is suggested that use of a model as a function of potential evaporation (i.e. calculated β') indicated a dependence of ∑Es on the atmospheric evaporative demand, which is mainly driven by net radiation and vapour removal characteristics under the prevailing weather conditions.

Nevertheless, the application of cumulative potential evaporation relationships has appreciable usefulness in estimating actual soil evaporation under field conditions for incomplete cover of IRWH. The studies of Jackson *et al. (*1976), Gill and Prihar (1983) and Stroosnijder (1987) found that models using cumulative potential evaporation ($\sum E_{pot}^{0.5}$) were very reliable, despite the popular usage of the Ritchie model in various other studies for estimating soil evaporation. Hattingh (1993) also found the model of Boesten & Stroosnijder (1986) to be very reliable, but claims that the Ritchie (1972) model performed better.

5.4 Conclusion

The method developed in this study has been shown to provide a practical *in situ* Es measurement using microlysimeters beneath maize canopy for the tillage of IRWH. In addition, there had been limited information in achieving Es measurements and estimation from the sub-section of the basin and runoff area under IRWH technique. Therefore in this study, evaluation of empirical models was performed in order to estimate the physical parameters of evaporation in bare and mulched soil surfaces in terms of time and potential evaporation $(t)^{-0.5}$ and $(\sum E_{pot})^{-0.5}$) for different positions across basin to runoff area of IRWH.

From the result the amount of Es reduction was determined by change in atmospheric conditions and ability of the surface treatments. Thus, all DCs showed highly significant differences on the total Es. Among the surface treatments (RSL and ML), only the ML showed a significant difference with higher total Es values in bare treatments, but the magnitude of Es reduction from different mulch levels had shown no statistical variations. This is probably due to the influence of evaporation processes on stage-1 and stage-2 for sandy loam soil of the experimental site with a high infiltration capacity. Even though the RSL did not show significant differences, the narrow RSL-1 was less restrictive in reduction of Es. The wide RSL-3 and RSL-2 reduced total Es by about 7-8% and 3-9% compared to narrow RSL-1. However, the combined effect ML and CS (positions) was detected with average Es reduction of 2.7, 1.5 and 1.4 mm d^{-1} for DC-1, 2 and 3, respectively. The major contribution for the interactive effect on Es was due to lower Es restrictive properties of bare FC-BA and higher Es restrictive properties of the mulched PC-RA sections of the runoff.

The present experiment on Es beneath maize canopy also gave a better insight into the range of variations in α' and β values in terms of time and E_{pot}, for different position of IRWH in fine sandy loam soils of Kenilworth Bainsvlei ecotope of the semi-arid area. In all the treatments the simulated ∑Es were underestimated by the Ritchie model and in contrast overestimated by the Stroosnijder model. Moreover, this study indicated that the time (α' model) performed well to estimate ∑Es from the basin area and the potential evaporation (β' model) from the unshaded runoff strips. However the consideration of weather parameters may have an advantage, since the microclimate of the cropping system changes according to surface treatments in the system of

IRWH. Therefore the microlysimeter used in the experiment made it possible to measure and compute daily and cumulative evaporation rate beneath maize canopies across the basin to runoff section of the IRWH structures. Moreover, the effect of surface treatments, such as mulching along with various canopy shading cover was confirmed in reducing evaporation rate to evaluate Es values within the maize field.

CHAPTER 6

Deriving Empirical Models to Estimate Soil Water Evaporation as Influenced by "*dry-mulch*" and "*green-mulch*" Cover of a Maize Canopy

6.1 Introduction

The amount of soil water lost to the atmosphere via soil water evaporation (Es) from beneath a crop canopy is highly variable on day to day as well as through the growth stages. In row crops like maize (*Zea mays* L.), Es was estimated to be as high as 50% of evapotranspiration under fully ploughed (Allen, 1990; Papendick and Campbell, 1990; Pilbeam *et al.,* 1995). However, under another maize system Klocke *et al.* (1990) reported that soil evaporation was only 30% of the total evapotranspiration during the growing season in western central Nebraska, USA. In semi-arid areas of South Africa, Bennie *et al.* (1994) claimed that soil evaporation could account for between 60% - 85% of the rainfall. Therefore, a better understanding of soil evaporation losses is needed to lead to the development of alternative production systems that can improve crop productivity in semi-arid climates.

As evaporation from the soil surface can be a major component of a cropping soil water balance, further studies of water balance and water use by crops grown under rainfed conditions, are needed to obtain some measurements or estimation of soil water evaporation (Es) from the cropped area. To assess the value of crop management practices to reduce Es loss, Es must be accurately measured or estimated. Evaporation from the cropped field under the system of IRWH is also influenced by the interaction of potential evaporation, amount of canopy cover, current soil water content (Wallace *et al.,* 1993; Todd *et al.,* 1991; Stroosnijder, 2003) and the position in basin area or runoff strip sections together with some other cultural practices. Of the strategies included in the technique of IRWH, the selection of mulching levels and optimum runoff length may be used to modify the water lost by evaporation from soil surface in semi-arid areas, which ia working against the water collection harvesting principles.

Various approaches have been used to estimate the soil evaporation from beneath the canopy. For example, the microlysimeter method provided an estimation of evaporation from beneath the canopy of growing crops (Boast and Robertson, 1982; Walker, 1983; Hoffman, 1997; Allen, 1990; Yunusa *et al.*, 1993a). However, the microlysimeter method is rarely used for long period or for Es estimations through the whole cropping season (Leuning *et al.,* 1994, Eastham *et al.,* 1999; Eastham and Gregory, 2000). As a result, alternative methods for estimating Es using either empirical (Adams *et al.,* 1976, Cooper *et al.,* 1983), semi-analytical (Ritchie, 1972) or modelling approaches (Lascano and van Bavel, 1986; Wallace *et al*., 1999) have been adopted in different studies of Es beneath crop canopies. Different approaches were suitable for different cropping systems, and only a few Es studies exist where comparisons were made for row crops (Admas *et al.,* 1976; Yunusa *et al.,* 1994; Eastham and Gregory, 2000, Philip and Mustafa, 2005). Furthermore, for the last two decades in the studies of the IRWH technique, Es has been considered a major component when evaluating different management practices (Hensley *et al.,* 2000, Botha *et al.,* 2003; van Rensburg *et al.,* 2005, Nhlabathi, 2010, Zerizghy *et al.,* 2011). Nevertheless, it seems that more investigations concerning the effect of shading ("*green-mulch*") and stover mulch ("*dry-mulch*") in suppressing Es are required to improve water management practices.

The usual effect of mulches or crop residue and/or shading is to lower the maximum soil temperature because of the greater reflection and lower penetration or absorption of solar radiation and that they have a lower thermal conductivity than the soil (Horton *et al.,* 1996; van Donk and Tollner, 2000). Reduction in evaporative losses with mulch or shading is also influenced by soil type, atmospheric evaporative demand, amount of mulch applied, precipitation pattern as well as other local climatic factors and cultural practices (Philip and Mustafa, 2005). Therefore, the reduction of soil evaporation by mulch or shading has been related to the percentage of surface cover (Adams *et al.,* 1976). Prihar *et al.* (1996) estimated a reduced maximum evaporation rate from mulch covered soils of different soil textures by using exponential fit functions of Es against percentage cover. The shading of the soil surface by the crop canopy could then be a substitute for the same type of protective effect of mulch cover (Unger and Jones, 1981). Therefore, both shading and mulch application ("*green-mulch* " and "*dry-mulch*") have been observed to favourably lower the soil water evaporation from a cropped land and are expected to increase water use efficiency in dryland farming.

The hypothesis of the study is that, the Es from a fine sandy loam soil of Bainsvlei Kenilworth ecotope, is reduced by both a complete organic stover mulch cover on the runoff strips and the crop canopy shading. Therefore, the objective of the study was:

- to develop empirical models to estimate cumulative soil evaporation across the basin and runoff sections beneath a maize canopy as influenced by varying amount of stover mulch ("*dry-mulch*") and canopy shading ("*green-mulch*") under the IRWH technique.

6.2 Materials and methods

6.2.1 Experimental layout

For this experiment, all the RSL treatments and three of the ML treatments, *viz*. 0%, 39% and 96%, were used to develop empirical relationships and to estimate cumulative soil water evaporation on every 1 m section length across the basin into the runoff area for the growing seasons, 2007/08 and 2008/09. The positions of the measurements were presented in schematic diagram in Chapter 5, Section 5.2.1 (Fig. 5.1).

6.2.2 Measurements and approaches

Growth stages: The phenological growth stages (as described in Chapter 2 Section 2.3) represent emergence to late vegetative (GS-I), late vegetative to tasseling (GS-II), tasseling to grain-filling (GS-III) and grain-filling to maturity or harvesting (GS-IV)

Weather variables: Weather data from the automatic weather station (AWS) on site was used to calculate the reference evapotranspiration, ETo FAO-56 Penman Monteith equation (Allen *et al.*, 1998) in order to compute (×1.1) daily potential evapotranspiration, ET_{pot} during each growing period at the experimental site (described in Chapter 5 Section 5.3).

Mulch application: The dry maize stover mulch was applied evenly only over the runoff section at several levels varying from bare (0%) to the maximum mulch level of 96% (described in Chapter 2, Section 2.3.1). The mulch application was done only prior to the second cropping season (2008/09).

Leaf area**:** Leaf area was used as an indicator of canopy development and shading. In the present study, leaf area (LA) measurements were performed from 25 DAP until the crop attain maximum plant growth at 10 days interval (described in Chapter 2 Section 2.3.2). An index was calculated as a ratio of measured leaf area over the basin land area only, (the same unit area for all RSL treatments) and so it is denoted as "BLAR". This different BLAR calculation, which only includes the basin unit land area, can help to categorize the effect of shading cover of a maize canopy across different RSL treatments as there are effectively a range of plant densities over basin area. The range of plant densities in the basin include 3.3, 4.1, 4.9 and 6.4 plants m^{-2} for RSL of 1, 1.5, 2 and 3 m, respectively, but effectively give the same total plant population across a hectare of land under IRWH.

Leaf area measurement in 2007/08 cropping season was only done once at flowering (65 DAP), and then interpolated to generate LA for the cropping season with a linear relationship between all RSL treatments (n=4) of the two seasons, which had a strong correlation (R^2=0.94). As a result, linear functions describing the development of BLAR of each RSL treatment throughout the growing period were developed (Appendix 6.1).

Canopy shading**:** Based on the results of LA obtained from the field measurement, an interpolation was made to extend to daily values throughout the growing period. This was implemented by a general procedure by constructing the crop coefficient curve during the growing period. That was derived from the four distinct growth stages for a medium maturing maize crop variety, as given in Allen *et al.* (1998). Hence, the numerical determination of the daily BLAR values was used to estimate the shading cover effect (CS) of a maize canopy. In the relationship, the assumption was made that a BLAR of 3 is proportional to full canopy cover for maize crop. Todd *et al.* (1991) and Allen (1990) suggested that from low plant population of a row planted maize crop, the full coverage probably will not exceed LAI of 3. Thus, the canopy shading effect as a shading cover percentage (CS%) is linked to the plant leaf area ratio values, by assuming that BLAR of 3 is proportional to full coverage.

Soil water evaporation**:** Evaporation of water from the soil surface beneath a crop canopy was measured using microlysimeters containing undisturbed soil samples during three drying cycles

(DC) each after a rain event. The periods selected for soil evaporation measurement were after the crop had reached its maximum canopy cover during the second season of the experiment (2008/09). The detail Es measurement procedures and the position of the microlysimeter measurement are described in Chapter 2, Section 2.2.2 and Chapter 5, Section 5.2.2 and 5.3.1.1.

6.2.3 Empirical relationships for model development

For the estimation of cumulative soil water evaporation (∑Es) during the crop growing period, the potential evaporation, leaf area induced canopy shading effect, mulching levels and soil characteristic parameter were considered. Soil surface area shaded by the canopy was computed as a function of BLAR, thus the canopy structure plays a significant role for improved solar radiation interception and consequently affect light availability for growth (Maddonni *et al.*, 2006), It is assumed that, plant cover provided by the canopy that reduces the Es is directly related to the mulch cover reducing effect on Es. The combined effect of surface treatments (mulch and shading cover) in reducing the cumulative evaporation were used to determine the estimated cumulative evaporation during the growing period for different positions in basin and across the runoff section.

For this study, a soil evaporation characteristic parameter for the experimental site was adopted by considering the Stroosnijder model for β' value (see Chapter 5, Section 5.3.1). Thus, for the soil of this experiment as a representative for bare plots (without mulch and shading effect) a central part of RSL-3 (RA2) were taken for computing Es. The average value of β' was = 1.87 $mm^{0.5}$, i.e. calculated from DC-1, β'= 1.91 $mm^{0.5}$ and DC-2 β'= 1.82 $mm^{0.5}$.

Using these newly developed models (Eqs. 6.2 and 6.3), calculations were made to estimate daily ∑Es by assuming that on a specific day the soil is wet to a considerable soil depth (at least top part of the surface soil 100 to mm deep) after a rainfall event. The soil wetting was assumed to occur at day n for a rain event. In this study three additional assumptions were taken into account for the calculation of daily ∑Es that depends on the effective rain ($RF_{(eff)}$), *viz.*

i) When the amount of daily rain > 6.5 mm ($RF_{(eff)} \geq 6.5$ mm), it is assumed that the soil is fully wet again and begins a drying cycle; and

ii) When the amount of daily rain is not fully effective (3 mm $\leq RF_{(eff)} < 6.5$ mm) it means that the rain does not entirely rewet the dried soil surface. In order to take this into consideration, an option used by Boesten and Stroosnijder (1986) was adopted where $\sum E_{pot(n)} = \sum E_{pot(n-1)} + E_{pot(n)} - RF_{(n)}$. This implies that a relatively small amount of rain only slightly lowers the increase in $\sum E_{pot}$ that contributed to actual Es.

iii) In the case of small rain events of less than 3 mm ($RF_{(eff)} < 3$ mm), it was considered that this small amount of rain was not enough to rewet the dried soil.

Thus, all options (i-iii) were included accordingly, i.e. calculations of ∑Es were made for 16 and 13 rain events using option (i) and 6 and 10 rain events using option (ii) for the growing periods 2007/08 and 2008/09, respectively. For the construction of the empirical models during 2008/09 cropping season a ∑Es data set for DC-2 was utilized to generate effects of CS and ML. Furthermore, the performance of the Es empirical models were verified by using the combined data set from DC-1 and DC-3 (2008/09) for the basin and runoff area. The DCs had higher evaporative demand in DC-1 and lower in DC-3 compared to DC-2 (Chapter 5, Section 5.3.1, and Table 5.1).

6.2.4 Statistical analysis method

From the measured leaf area data at an interval of 10 days (from 25 – 65 DAP), a statistical analysis was done with the results of BLAR to analyze the effect of RSL and ML treatments on each measurement day (DAP), using the statistical software SAS 9.1.3 for Windows (SAS Inst. Inc., 2006). In this analysis, Randomized Complete Block Design (RCBD) replicated three times was used and means and LSD for the main treatment effects were computed. In a similar way, statistical analysis was carried out on the calculated values of canopy shading percentage (CS%) for the effect on RSL treatments and between the two cropping season. For developing empirical relationships both linear and exponential functions of regression procedures were applied. Furthermore, from the model results of estimated of ∑Es, statistical comparisons were also made between treatments, using the same procedure. For the evaluation of the models, measured and estimated ∑Es values were compared using simple regression procedures and mean statistics as given by Willmott (1981; 1982).

6.3 Results and discussion

6.3.1 Rainfall and potential evapotranspiration

The average rainfall over two seasons was 266.2 mm which is 104.7 mm lower than the long term mean rainfall for the full growing period (GP) (Table 6.1). The second growing season had lower rainfall than the first growing season, but they were both dry years. The rainfall during the GS-I and GS-II of 2007/08 was less than the rainfall of the same GSs in 2008/09 cropping season. However, in GS-III the rainfall for the first growing season was much higher (3 times) than that in the second growing season. The amount of rainfall received during the GS-III therefore comprises 37.0% and 12.4% of the total rainfall received during the growing seasons 2007/08 and 2008/09, respectively. In the second growing season, the water deficit was during the reproductive stages, which had a greater influence on the yield. Passioura (2006) determined that water deficit occurring at any one of the critical stages, will cause a reduction in the total dry matter yield. In order to satisfy the evaporative demand of the crop, the required amount of rainfall needs to be suitably distributed across all the different growth stages unless water can be supplied by stored soil water.

Table 6.1 Rainfall (RF) potential evaporation (E_{pot}) and Aridity Index (AI) for the four growth stages for two maize growing seasons (2007/08 & 2008/09) at Kenilworth Bainsvlei.

Parameters	Cropping Season	Crop growth stages				
		GS-I (0-45)	GS-II (46-70)	GS-III (71-105)	GS-IV (106-150)	GP
RF(mm)	2007/08	88.9	52.6	104.7	36.3	282.5
	2008/09	114.5	64.6	30.9	39.8	249.8
	Mean (2 yrs)	101.7	58.6	67.8	38.1	266.2
	LT mean					370.9
E_{pot}(mm)	2007/08	281.7	134.1	153.3	151.3	720.4
	2008/09	294.7	88.0	138.1	129.3	650.1
	Mean (2 yrs)	288.2	111.1	145.7	140.3	685.3
	LT mean					1283.2
AI	2007/08	0.32	0.39	0.68	0.24	0.392
	2008/09	0.39	0.73	0.22	0.32	0.384
	Mean (2 yrs)	0.36	0.56	0.45	0.28	0.388
	LT mean					0.289

*LT is the long-term and GP is growing period. Data set from 2000-2009, source ARC-ISCW Climate Data Bank. *AI calculated Aridity Index = (RF/* E_{pot}*)*

The amount of E_{pot} for the second season was lower by 70.3 mm compared to the first cropping seasons (Table 6.1). Although both seasons show a similar average aridity index (AI) of 0.38 and 0.39 during the growing periods, but the growth stages have marked differences (Table 6.1).

There is a well-defined water deficit (AI of less than 0.25) during GS-IV in the first season and during GS-III in the second season, dropping from relatively higher AI (>0.65) in the previous growth stages. However in both years, the higher AI had only lasted through one growth stage as the beginning of the season AI was 0.39 in both years.

The long-term precipitation amount is nearly sufficient for maize production (Hensley *et al.*, 2000), but the distribution and intensities of the rainfall vary across the various growth stages, as a result it is usually inadequate to support a good harvest in semi-arid areas. High evaporative demand and the erratic nature of the rainfall causes semi-arid climates resulting in low productivity of maize, particularly due to high evaporative demand during the tasseling and grain filling stages (Hensley *et al.*, 2000; Passioura, 2006). Thus, it is important to apply cultural management practices to reduce soil evaporation losses that would reserve more water for the crop for better productivity.

6.3.2 Effects of canopy shade and mulch cover

6.3.2.1 Leaf area

The measurement of LA is an important parameter in determining the cover effect of the crop beneath the canopy. The statistical analysis of the mean value of BLAR at 10 day intervals showed a significant difference at P value < 0.0001 for the effect of RSL treatments, but ML treatments had no significant difference (Table 6.2). Evidently, there was a significant difference between the BLAR through the season (with DAP), as expected, although there was no significant difference detected within between the first two measurements (25 and 35 DAP) when the crop is in the vegetative stage (GS-I).

The canopy developed rapidly reached a plateau at 55 - 65 DAP for all treatments of wide (RSL-2 & 3) and narrow (RSL-1 & 1.5) with different mulching levels. The highest BLAR was obtained from RSL-3 as all plants are concentrated in the basin area compared to RSL-1 where plants are spread evenly over the whole treatment area. This implies that, BLAR were generally greater for wider RSL treatments compared to narrow RSL treatments because of the plant densities per unit basin area were greater in wider runoff strip lengths. The BLAR was highest (2.47) in RSL-3 as it had the highest density of plants (6.4 plants m^{-2} in basin area) and the RSL-

2 at BLAR 1.76 and RSL-1.5 at 1.40 and the lowest density RSL-1 (3.3 plants m^{-2} in basin area) at BLAR = 1.18 (Table. 6.2). There was no effect of mulch over the runoff strip of any length on the BLAR for each RSL group as the competition for radiation and density of plants in the basin area was not different.

Table 6.2 Effect of runoff strip length (RSL) and mulch level (ML) on measured basin leaf area ratio (BLAR) of the basin area during growing period.

Treatments	Days after planting (DAP)					Mean
	25	35	45	55	65	
a) Runoff strip length (RSL)						
1 m	0.04	0.17	0.38	1.00	1.18	0.55c
1.5 m	0.06	0.15	0.49	1.10	1.40	0.64c
2 m	0.08	0.20	0.60	1.60	1.76	0.85b
3 m	0.11	0.33	0.85	2.21	2.47	1.19a
b) Mulch level (ML)						
0% (bare)	0.07	0.22	0.56	1.43	1.72	0.80
12%	0.07	0.21	0.54	1.45	1.68	0.79
39%	0.08	0.22	0.56	1.50	1.69	0.81
64%	0.08	0.21	0.62	1.52	1.73	0.83
96%	0.07	0.20	0.61	1.47	1.70	0.81
Mean	0.07d	0.21d	0.58c	1.48b	1.70a	
Interaction (RSL×ML) ***LSD:*** DAP = 0.15 RSL = 0.13 ML = ns RSL*ML = ns						

For example, the plateau BLAR on wide RSL-3 treatments were 52% and 43% greater compared to narrow RSL-1 and RSL-1.5 treatments, respectively. Todd *et al.* (1991) found that peak LAI for maize to be at 60 - 65 days after planting at a range of 2.50 – 3.00. In another study of sparse maize rows, Tuzet and Wilson (2002) claimed that within a uniform field of maize the lowest overall LAI value was 0.09 whereas, in contrast, the LAI of the highest cover was found to be 2.50. This value is in agreement with the average BLAR of 2.47 for RSL-3 at 65 DAP (Table 6.2). Therefore, it is presumed that, the BLAR values of this experiment can be used to estimate canopy shade cover during the growing period.

6.3.2.2 Canopy shade cover development

The development of soil surface cover through canopy shading can improve soil water availability by reducing soil evaporation. In general the CS% follows a sigmoid curve as it is developed from the leaf area expansion of the crop. However, the canopy shading cover percentage (CS%) varied according to the RSL during both growing seasons (Fig. 6.1). There was a highly significant difference between the growing seasons and among RSL treatments on the effect of canopy shading. The highest CS% was observed in a wide treatment compared to narrow strips during both of the growing seasons. The first growing season showed much higher canopy shading cover in each of the RSL treatments from generated leaf area values. The RSL-3 CS% values reached maximum at about 65 DAP in all treatments with CS% values of 47% - 94% and 40% - 79% for the first and second seasons (Fig. 6.1). The lowest BLAR on 25 DAP was 0.04 which was equivalent to 1.4% and the maximum BLAR on 65 DAP, was 2.58, which becomes a canopy cover percentage of 86%.

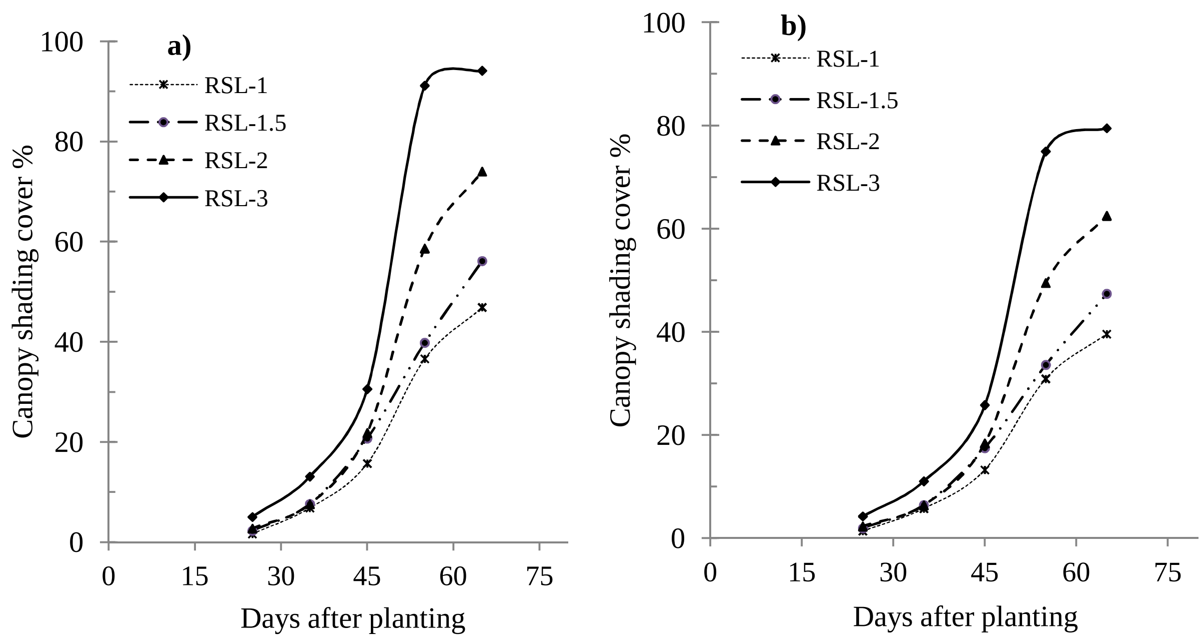


Figure 6.1 Canopy shading cover percentage for different RSL treatments during cropping seasons (a) 2007/08 and (b) 2008/2009.

6.3.2.3 Canopy shade effect related to mulch cover

In this study the assumption was made that Es is affected by canopy shading and mulch in the same manner. The leaf canopy is considered to be a type of “green mulch” that covers the soil and prevents the penetration of solar radiation to the soil surface, just as the stover mulch cover “dry mulch” would do. Therefore both “green mulch” and “dry mulch” effects were used to establish Es dependence on the two surface treatments of RSL and ML, respectively, and consequently develop relationships for soil evaporation rate under the canopy shaded and mulch cover, using the two data sets of Es, as an assumption:

- The bare basin Es with highest plant density (RSL-3 basin) as a full leaf canopy was assigned to be equal to the Es from the centre of the RSL-3 plot with highest mulch level (ML96%) where there is no plant cover at the centre of the runoff strip (RA-UC).

These Es measured values were then compared with green and dry mulches (Fig. 6.2). The relationship between canopy shading and mulch level was consequently best described by straight line (Fig. 6.2) which implies that the effect of shading and/or mulching can reduce soil evaporation under the maize crop.

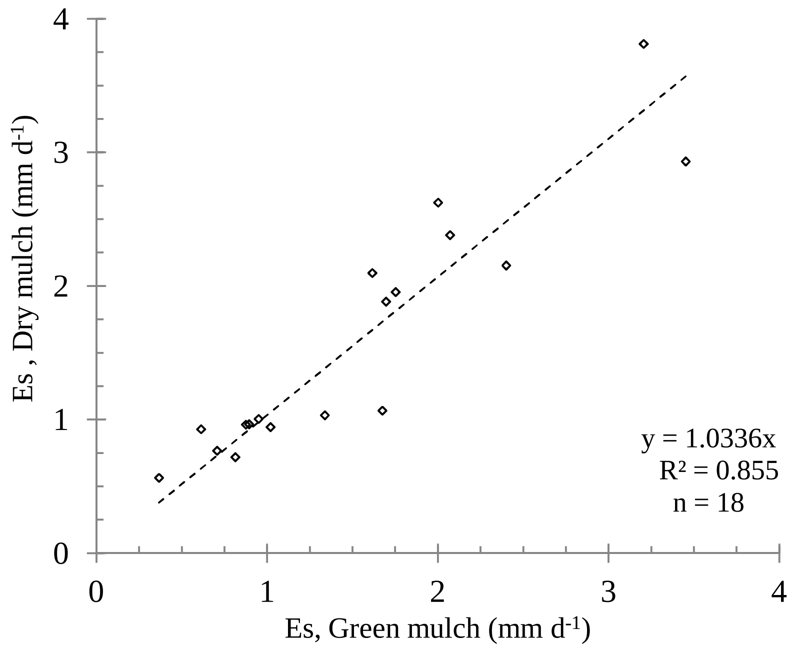


Figure 6.2 Measurement of daily Es values under the canopy as "*green-mulch*", i.e. from bare full shaded (RSL-3 Basin) basin area compared with the Es from "*dry mulch*" of ML96% with no canopy cover (RSL-3, RA-UC).

From Fig. 6.2, therefore, it was confirmed that, as the graph shows soil evaporation due to the effect of shading and mulch cover has a strong linear relationship with R^2 of 0.85. Hence, this relationship can confidently be used to evaluate the influence of shading (plant canopy cover) or the so called "*green-mulch*" and mulch material applications or "*dry mulch*" in reducing Es in the maize field with an alternative basin and runoff area arrangement as in the case of IRWH. Adams (1976) has shown that the percentage of shading can be determined by using LAI of different row spacing and variation in plant population or by applying any available methods that can shade the soil surface of a crop land during the growing season (Anderson, 1971). Hence, in this study, for a maize crop under IRWH system this can provide an alternative approach to estimate the canopy shade effect on soil water evaporation within the maize crop field.

6.3.3 Alternative method to calculate soil surface evaporation

For quantitative estimation of potential and actual evaporation losses from the soil surface under the crop canopy it is often required to assess the value of crop management practices such as the technique of IRWH. In order to consider the estimation of daily or seasonal Es, one can apply simple empirical relationships. In this present study assumptions were taken from the standard approach to calculate crop evapotranspiration (ETc), since the soil water evaporation is part of ETc, where it is partitioned into Ev and Es. On the other hand, effects of the weather conditions on the evaporation are incorporated into ETo (Monteith and Unsworth, 1990). Hence the common procedure used to determine the ETc is by using a crop coefficient factor (Kc) i.e. multiplying ETo by Kc (Allen et *al.*, 1998). Furthermore, to estimate Es Boesten and Stroosnijder (1986) proposed to use an evaporation characteristics soil parameter containing a single parameter (β'), for bare soils assuming that it evaporate at potential rate. However in this study, as an alternative to calculate cumulative Es from different surface treatments beneath the maize canopy, the value of an addition coefficient factor (K_{cover}) for green mulch cover such as shading and/or dry mulch were incorporated into Stroosnijder model as follows:

$$\sum Es = K_{cover}\beta' \times \sqrt{\sum E_{pot}} \qquad \textbf{6.1}$$

Therefore, empirical equations were used to estimate ∑Es, taking into consideration the reducing effect of CS and ML in the IRWH system. These assumptions were different for basin areas, with only shading effect and for the runoff areas with the effect of mulch under various shading, as follows:

- To obtain a coefficient for green mulch factor (K_{cover}) the soil evaporation was calculated as a function of percent shading (n=5) for the basin of each RSL treatments (39.5%, 47.5%, 62.5% and 79.5% for RSL-1, 1.5, 2 and 3 m respectively) together with the unshaded section in the central part of RSL-3 (UC), where one assumes CS% = 0. It was assumed that the Es could reach a maximum (∑Es(max)) on bare and unshaded, with K_{cover} = 1. Thus, the data points of ∑Es for the basin area were fitted to ∑Es/∑Es(max) against CS%, in order to obtain Kc factor, K_{cover} ranging from 0 – 1.

- The mulch cover effect on the runoff area was categorised accordingly to FC, PC and UC at three levels of mulch cover (n=9). In this regard a multiple linear regression was applied for the combined effect of CS and ML for different positions, simultaneously. Then, a similar procedure was applied to obtain a crop coefficient (K_{cover}) values for the runoff area with both ML and CS effects on Es. The resulting equations are as follows:

Basin area: $\sum Es = -0.1357CS + 19.564$ (R2= 0. 92) **6.2**

Runoff area: $\sum Es = -0.0912ML - 0.0117CS + 17.163$ (R2= 0. 84) **6.3**

Based on these assumptions using the linear relationships (Eqs. 6.2 and 6.3) an interpolation was performed to obtain Kc values for each treatment under the effect of ML and CS, as listed in Table 6.2. These K_{cover} values will be used to calculate ∑Es together with the Stroosnijder model.

Table 6.3 Values of coefficients factor (K_{cover}) for canopy shading for basin area and mulch cover together with shading effect for runoff area, as calculated from the ratio $\sum Es/\sum E_{max}$ and as function of CS% and ML%.

Mulch or canopy shade cover (%)	**Bare**	**12 %**	**39or39.5 %**	**47.5 %**	**62or64 %**	**79.5 %**	**96 %**
Basin Area K_{cover}			0.92	0.73	0.56	0.33	
Runoff area K_{cover}							
FC	0.94	0.88	0.73		0.60		0.43
PC	0.97	0.91	0.76		0.63		0.46
UC	1.00	0.94	0.79		0.66		0.49

The canopy shade cover (CS) of 39.5%, 47.5, 62% and 79.5 correspond to the RSL of 1, 1.5, 2 and 3 m, respectively.

From the reference value of the bare UC where Es is expected to attain to the maximum ∑Es (∑Es(max), the K_{cover} values found were in the range of 0.33 – 0.92 and 0.43 – 0.97 for the basin and runoff area, respectively. Thus in both cases the K_{cover} decreased with an increase of mulch and shading cover (Table 6.3). Shading by a maize canopy might be especially important in the system of IRWH, where the adjacent plant rows are of varying distance from each other between runoff strips. For the soil covered with mulch, the potential evaporation rate at the soil surface is reduced due to the cover effect of the mulching material ("*dry-mulch*"). Reducing evaporation from the soil surface is estimated by the linear relationships from the cumulative Es such that the fractional cover governs radiation energy interception and a soil parameter effect. Therefore, the implication of these new alternative models developed in this study is the inclusion of both atmospheric weather conditions and surface treatments. Allen *et al.* (1998) discussed that E_{pot}

depends mainly on net radiation and water vapour removal charactertics but it also depends to a lesser extent on the properties of the soil (van Bavel and Hillel, 1976; Boesten and Stroosnijder, 1986). The empirical relationships of the cumulative potential and actual soil evaporation then contribute to include the effect of surface treatments (Jalota and Prihar, 1998).

In the present study therefore, the cumulative or daily Es for the whole growing period was determined using the developed empirical equations by relating potential evapotranspiration and the effect that the surface treatments had in reducing Es losses at a field level. Consequently, it is an important step to perform an evaluation of the empirical models using the available field data sets.

6.3.4 Evaluation of the empirical models

Validation of the empirical models was made using the field data obtained during the Es experiments of DC-1 and DC-3 which had effects of shade and mulch (Fig. 6.3). The results of the performance statistics showed predicted ∑Es from the combined data set of the basin and runoff area with R^2 of 0.59. However, the critical RMSEu/RMSE ratio is fairly good (> 0.52), as is the acceptable D-index value. However, the predicted ∑Es values are poorly scattered around a 1:1 line fit, and resulted in underestimation of about 24%. The RMSE and MAE values were found to be 2.164 and 1.992 mm. These high error values were probably due to the complicated effects of shading together with the mulch cover in the IRWH system. Interestingly, the variation around 1:1 line was smaller for the bare UC runoff positions than the mulched and/or shaded positions. Nevertheless, from the statistical results of the validation procedure, it is concluded that the model for estimating ∑Es from different positions of the basins and across runoff area of the IRWH techniques can be used for computing the water balance components (Chapter 7).

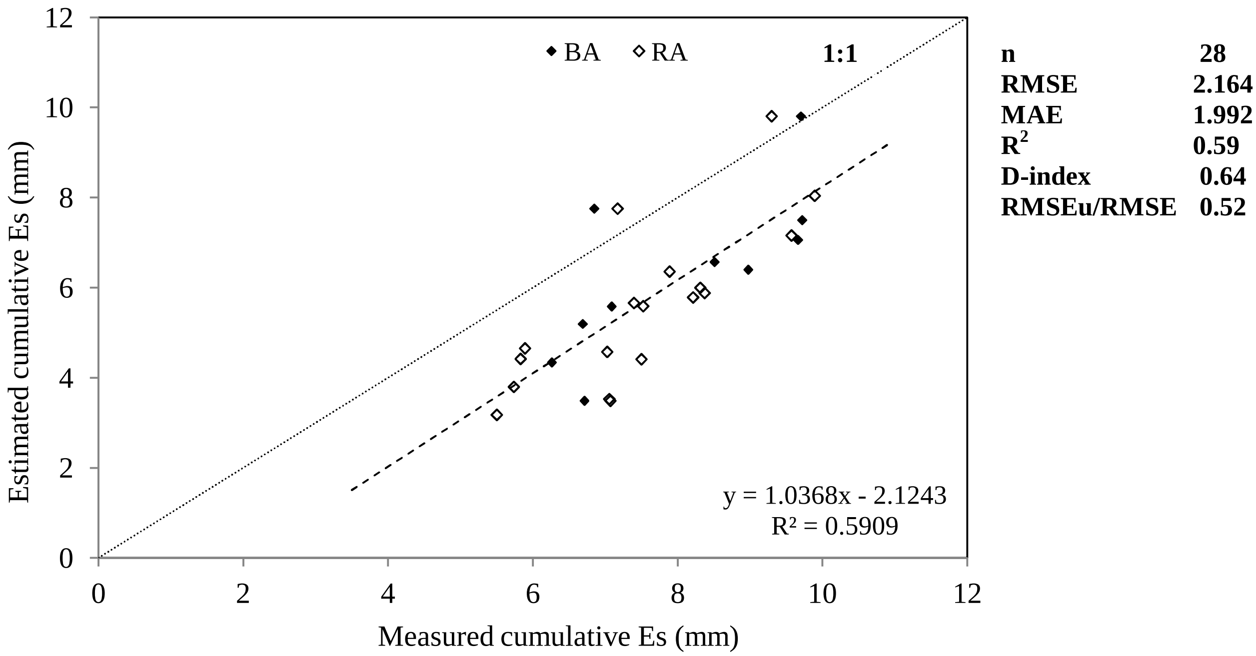


Figure 6.3 Evaluations of the measured versus estimated of cumulative soil evaporation for combined data set of the DC-1 and DC-3 for basin area (BA) (n=10) and runoff area (RA) (n=18) using equation 6.1.

6.3.5 Estimation of soil evaporation during the growth period

In the system of IRWH, Es is likely to be largely affected by the different positions between the rows and across the runoff area. Irrespective of different runoff lengths, the proportion of incident solar radiation intercepted by the canopy of the crop increases as the crop develops, consequently the reduction in evaporation from the soil surface accordingly increased. ∑Es calculated from the model for the basin and runoff area are presented in Figs. 6.4 to 6.6, according to different shading and mulch cover levels. Each RSL treatment curve can be described quite well by a second degree polynomial function ($R^2 > 0.98$). Besides the ∑Es results were summarized for each growth stage and then ∑Es represented as a proportion of seasonal rainfall and as a reduction from potential evapotranspiration (Appendices 6.2- 6.4).

6.3.5.1 Basin area soil evaporation

All the RSL treatments in both seasons showed a similar pattern with large ∑Es values for the first growing season (Fig. 6.4). There were highly significant differences ($P < 0.0001$) between the two growing seasons and among the RSL treatments. The highest ∑Es was estimated from the narrow treatments of RSL-1 with cumulative values of 173.4 mm and 152.2 mm for the growing seasons of 2007/08 and 2008/09, respectively. The lowest estimated amount of ∑Es was found for wide RSL-3 with 62.2 and 54.6 mm during first and second growing seasons, respectively (Fig. 6.4). For the two cropping seasons, the ∑Es as percentage of seasonal rainfall for the wide (RSL-3) and narrow (RSL-1) runoff strips were about 22% and 61% (Appendix 6.1). This indicates that, in both seasons the basin area seasonal cumulative evaporation reduction, CER (CER=1-(∑Es/$\sum E_{pot}$)) was increased from 64% to 87% for the first season and 77% to 92% for the second season with an increase in length of the runoff strip (Appendix 6.2). This is due to the fact that the effective shading cover of the basin area beneath the maize canopy increased due to high number of plants in larger runoff strip plots.

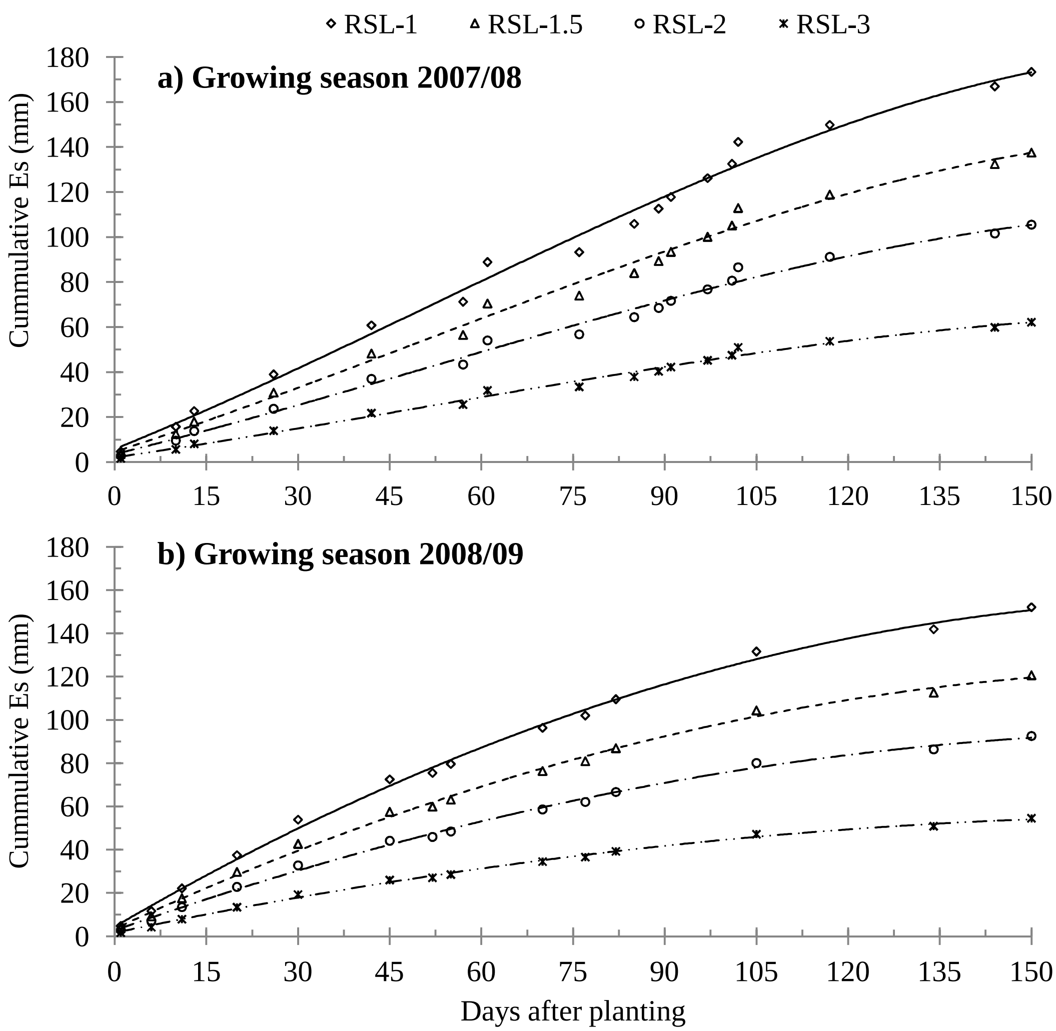


Figure 6.4 Seasonal estimation of ∑Es in the basin area of different RSL treatments for both growing season a) 2007/08 and b) 2008/09.

In the basin area of the wide treatments with higher plant density, the potential benefit of reducing Es, was recognized due to higher shading effect compared to the basin of the narrow strips. This implies that under dry conditions, the proportion of water lost to Es could be decreased and used for transpiration and subsequently, seasonal water use efficiency would be expected to increase for the wide RSL treatments. Moreover, under conditions, where rainfall is more plentiful or after a heavy rainstorm, the wide runoff may have a chance to infiltrate and store more water in the deep fine sandy loam soil profile of this experimental site. Conversely, the amount of rainwater to be collected in the basin area of wide runoff strips through in-field runoff was lower compared to basin areas with narrow strips (see Chapter 3 Section 3.3.2) and thus less Es also. Cooper *et al.* (1987) described the water loss by Es as a substantial component of the total water use under dry conditions. French and Schultz (1984) and Siddique *et al.* (1990) also focusing specifically on maize crops with sparse canopies (LAI < 2), found that Es losses were an important component of the soil water balance. This shows the importance of an accurate estimate of soil evaporation from the cropped area when determining water use by crops grown under rainfed conditions. It has been shown from the empirical ∑Es equation that the bare basin area (planting zone) for maize under IRWH technique with the wide runoff strip lost a lower proportion of the ET by Es, resulting in more water for Ev than from the narrow RSL. In contrast Philip and Mustafa (2005) suggested that with a high in-row leaf area and higher plant density competition for radiation and nutrients by the plants could result in elevated soil evaporation. However, in tropical and subtropical areas the availability of solar radiation is not a major limiting factor for crop growth and productivity compared to the scarce water resource.

In general, it can be stated that, the soil profile in the basin area potentially may have higher available water than that of the runoff area, in the system of IRWH, specially, after a rain and therefore, the basin area supplies greater quantities of water to meet evaporative demand. Evidence present in this study showed that, canopy structure in the basin area is likely to affect the magnitude of the evaporation losses from the soil beneath the maize canopy under IRWH (Chapter 5). This could also influence the available soil water for the efficient crop productivity (Chapter 7).

6.3.5.2 Runoff area soil evaporation

In this present study, unlike the bare basin area, the runoff strips were covered with various mulch levels to influence the evaporation from the soil. In addition, the runoff section was also affected by the degree of shading from either side of the row crops. Therefore the complicated part of the Es estimation is the runoff area beneath the maize canopy, as there is an interaction of these two simultaneous effects of mulch and shading cover. From Fig. 6.5, the ∑Es curves for different shading patterns over the runoff section show significant differences in both mulch and shading effect for the growing season 2008/09. Results showed that the highest ∑Es was estimated from the bare (ML0%) treatments with values of 165.4 mm from unshaded central part of RSL-3. The overall trend showed ∑Es was lower with more mulch cover. Therefore, the full mulch cover (96%) was found to be the most effective in reducing Es. In the partially shaded portion of RSL-2 and RSL-3 runoff strips, accumulating Es over the growing period gave higher values than fully shaded portions but lower than UC at various mulch levels (Appendix 6.3). For example, ∑Es from the fully shaded bare or fully mulched was lowered by about 5 mm and 10 mm compared to PC and UC runoff section. The main reason for the lower ∑Es for fully shaded narrow RSL is due to the fact of lower penetration of solar radiation and much lower air movement within the canopy that drive evaporation from the soil surface (see Chapter 8, Section 8.4.3 and Chapter 9, Section 9.3.5).

From the study of Es in IRWH techniques, Botha (2006) described how the higher organic mulch level could give crop roots enough time to extract a greater portion of water after each rainstorm compared to bare plots. This implies that, a lower amount of rainfall is used for Es. For example, in this experiment, the proportion of water loss from seasonal rainfall was about 62% and 64% for bare soils and as low as 28% and 30% for full mulch rate (MR96%) under full canopy and partially shaded positions of wide treatments (Appendix 6.3). This range of ∑Es over 2008/09 season, showed the good effects of IRWH management practices in restricting soil evaporation losses, that can lead to higher water use efficiency and consequently better yields (Chapter 7, Section 7.3.3.2). In a similar way, all runoff treatments showed high ∑Es during GS-I and lower ∑Es in later growth stages (GS-II to GS-IV). Thus, GS-I comprises about 48% of the total seasonal Es (Appendix 6.2), when canopy leaf development and radiation interception were low,

∑Es dominates evapotranspiration (Tanner and Jury, 1976; Cooper *et al.*, 1987; Yunusa *et al.*, 1993b, Philip and Mustafa, 2005).

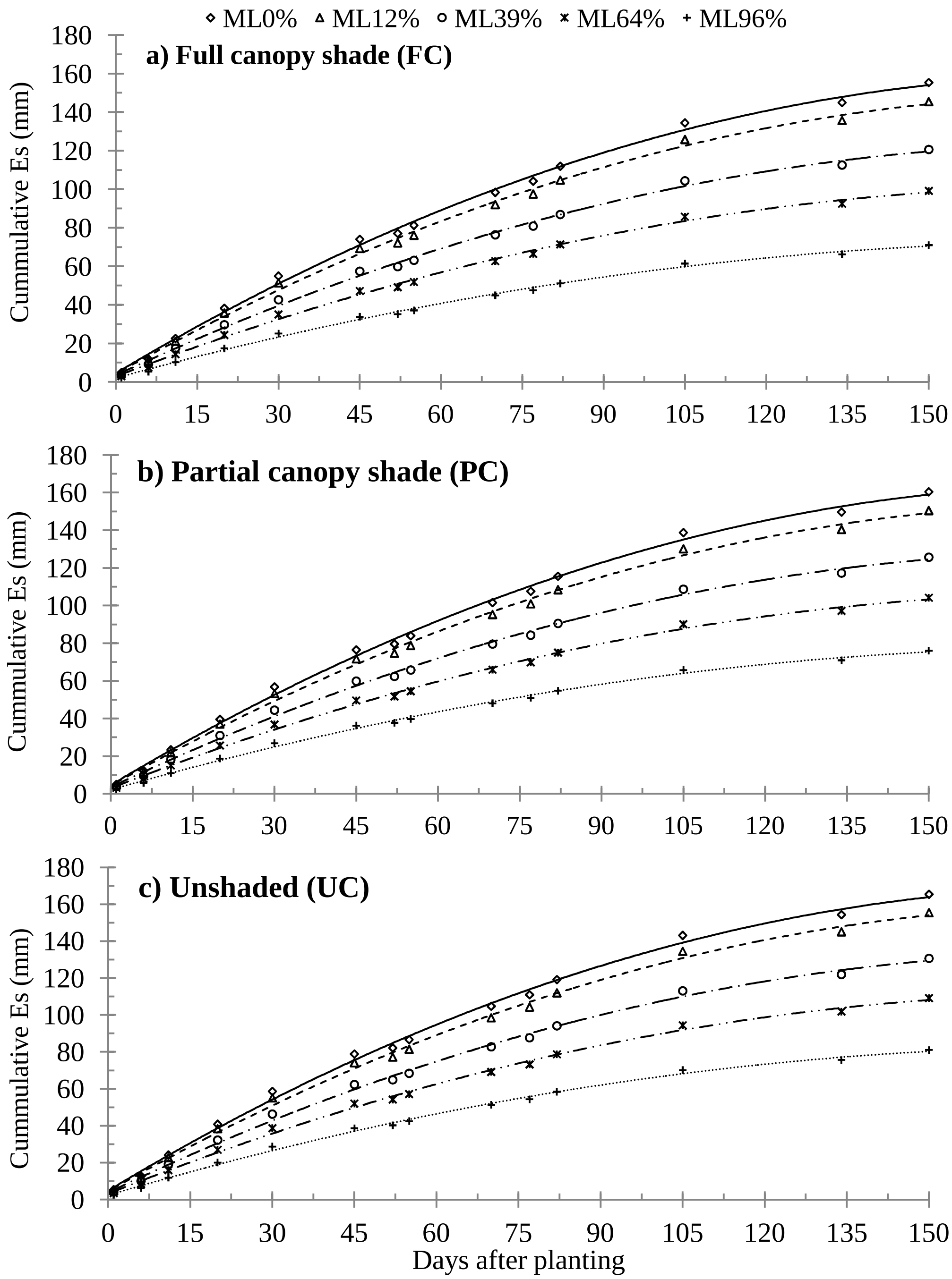


Figure 6.5 Seasonal estimation of ∑Es from the runoff area with different shading for growing season 2008/09, a) full canopy cover b) partial canopy cover c) unshaded portion of the runoff strip for RSL-3.

However, later in the season 92008/09), when the canopy was fully expanded and the soil surface was less frequently wet (during GS-III-IV), ∑Es becomes a lower component of total evapotranspiration (Eastham *et al.*, 1999).

In a similar manner, for the 2007/08 growing season without mulch application on the runoff strips, the range of Es was only due to the shading effect of the maize canopy (Fig. 6.6). The result showed that there was a significant difference between shading effect or positions on cumulative Es with LSD values of 1.99. In this particular season, the plant density was 33% higher than the following season hence the shading effect reduced Es by more than 63%, 61%. and 60% for FC, PC and UC positions of the runoff strips (Appendix 6.4). However, during the first season, ∑Es was much higher than the second growing season. The ∑Es proportion of the seasonal rainfall was about the same as the second season and ranged between 60% – 66%.

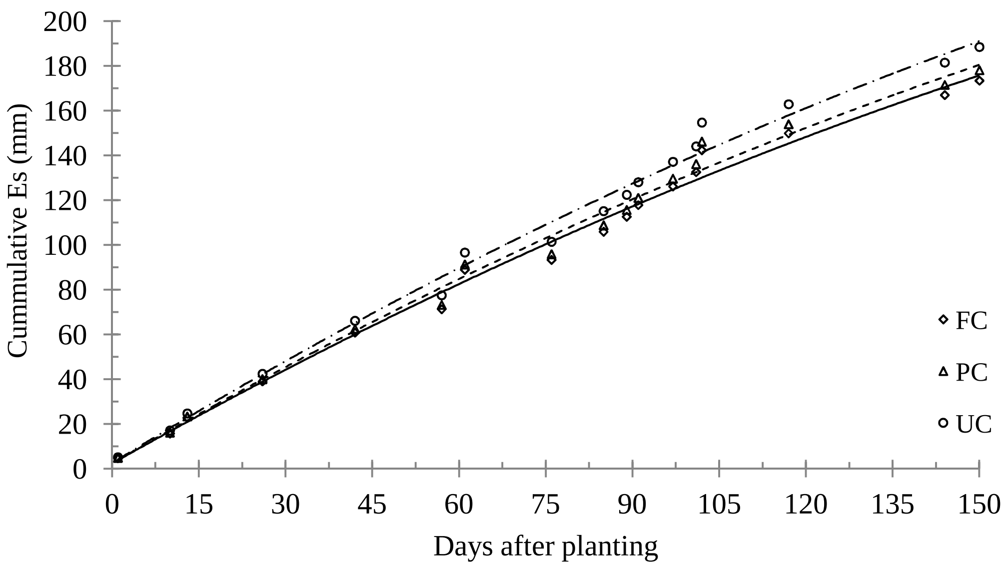


Figure 6.6 Seasonal estimation of ∑Es from the runoff area with different shading show growing season 2007/08 Full canopy cover (FC), partial canopy cover (PC) unshaded portion (UC) of the runoff.

Despite often considering the management practices to reduce evaporation losses, the shading may directly benefit the crop in regulating the radiation that directly hits the mulched surface. Thus, the shading effect reduces the temperature of the mulched surface and this decreases energy available to evaporate water. From the microclimate of the crop canopy point of view, the shading also has an indirect benefit over the mulched surface by lowering within canopy temperature and increasing the water vapour. This suggestion is in agreement with results in

Chapter 9, Section 9.3.4, when the crop under dry conditions experiencing higher water losses at higher temperatures with high water vapour than the cool day with lower temperatures with higher water vapour at canopy level. Leuning *et al. (*1994) described the advantage of higher water vapour in crop canopy and in the lower boundary layer of the plant community for moderating vapour pressure deficit (VPD), as a result preserving more water for transpiration, which directly contributed to productivity (Cooper *et al.*, 1983; Cooper *et al.*, 1987; Tennant and Hall, 2001).

6.4 Conclusion

Many techniques for measuring and models for estimating soil evaporation beneath crop canopies have been developed. However direct measurement of Es in the IRWH system is more difficult because this type cropping system consists of a variety of incomplete soil surface covers. The modelling of the soil evaporation from the sparse canopy of IRWH was complex, though others had developed measurement techniques for use in a semi-arid environment. In this present study, progress has been made by developing an empirical model of Es for conditions under a sparse maize canopy such as found in the IRWH technique. Furthermore, the ∑Es was evaluated as influenced by mulch ("*dry-mulch*") and shading ("*green-mulch*") of the basin area and various portions of the runoff area.

The results indicate that, the highest soil evaporation was found in the basin area of the narrow treatments with mean value of 173.4 and 152.2 mm during the first and second seasons, while the lowest ∑Es estimates were for wide runoff section treatments (RSL-3) with ∑Es of 62.2 and 54.6 mm for consecutive seasons. These ∑Es values from a basin area beneath a maize crop under IRWH amounted to about an average 42% of the seasonal rainfall. Furthermore, the estimated Es was reduced by 76.9% of the E_{pot} on the narrow (RSL-1) to a highest of 91.7% on the wide (RSL-3) runoff strips. This range is due to the large amount of shading from the maize crop canopy in the basin area according to different planting densities. In the runoff area, the highest ∑Es was found from bare soils with various shading cover effects and the full mulch (96%) was found to be the most effective in reducing soil evaporation. Thus, the ∑Es proportion of seasonal rainfall is about 62%, 64% and 66% from bare soil and as low as 28%, 30% and 32% for full mulch cover under full shaded (FC), partial canopy shaded (PC) and unshaded (UC) respectively. In contrast, in the first season without any mulch application, the ∑Es proportion of the seasonal rainfall ranged from 61% – 67%, which compares favourably with next season bare soil values.

Therefore, this study, has contributed relevant information to the partitioning of ET for the system of IRWH with basin area and runoff section area. Es reduction was influenced by the degree of both "*dry-mulch*" beneath the maize canopy and "*green mulch*". This implies that, reduction of ∑Es losses through surface cover techniques (RSL and ML) could promote improved water use efficiency, as more stored water is available in the root zone for transpiration.

CHAPTER 7

Application of Water Balance Model and Productivity Indices for Surface Treatment Management Strategies under In-field Rainwater Harvesting

7.1 Introduction

In arid and semi-arid areas, water is the most limiting resource for improving rainfed agricultural production. In semi-arid regions, rainfed agriculture is coping with unreliable rainfall, poor soils and recurrent droughts with subsequent crop and livestock production failure (Stroosnijder, 2003). In semi-arid areas climatic variability is at different temporal scales (Usman and Reason, 2004). High natural inter-annual climatic variability is expressed as droughts and floods; high in-season variability of rainfall leads to frequent dry spells (Usman and Reason, 2004). Improving rainwater productivity is one of the outstanding strategies for use in rainfed agriculture or dryland farming. However, in dryland farming, much of the productive rainwater is lost through runoff and soil evaporation (Es), resulting in extremely low rainwater productivity (Somme *et al.*, 2004). Oweis *et al.* (2001) suggested that in dryland agriculture over 50% of lost water could be recovered through improved water harvesting techniques. Farmers in the semi-arid areas have therefore developed strategies, including in-field rainwater harvesting (IRWH), to cope with these uncertain and erratic rainfall patterns.

In South Africa about 32% of the land area receives mean annual rainfall of less than 300 mm and almost 60% receives less than 500 mm per annum with erratic distribution, which increases the risk of crop failures (Schulze, 2006). In the semi-arid crop production areas in the central part of South Africa, the problem of low and erratic rainfall is exacerbated by two major factors, *viz*. high runoff and high atmospheric evaporative demand (Hensley *et al.*, 2000) which lead to high evaporation of water from the soil surface. These losses hamper the efficient use of available water for crop production and water losses need to be minimized in order to optimise rainwater productivity. Therefore, the approach of IRWH with appropriate cultural management practices (Hatibu *et al.*, 1995; Hensley *et al.*, 2000; Botha *et al.*, 2003; van Rensburg *et al.*, 2005) is an important consideration for rainfed agriculture and can be an adaptation method against climate change (Rockstrom *et al.*, 2007).

It has long been recognized that the maize crop yield under rainfed agriculture in semi-arid areas is dependent on soil water available for the crop. Minimization of the water losses and/or maximizing available water through collecting in-field runoff can offer an important opportunity for increasing crop yield (Bennie *et al.,* 1994; Hensley *et al.*, 2000; Botha *et al.,* 2003). From different studies of IRWH, ample studies of soil water balance, yield and water productivity evaluations have been done on a fixed 2 m runoff length relative to conventional tillage, however, there are limited measurements and studies over a range of runoff strip lengths and mulch level applications. For this reason, one needs to determine the appropriate water balance components for the specific environment and then to evaluate the suitability of the system for that specific environment and cropping conditions. In this study, therefore, IRWH with the effect of various mulch levels on different lengths of runoff strips will be evaluated using the soil water balance components and rainwater productivity. This study addresses the potential role of rainwater harvesting through major findings of run-on and estimation of soil evaporation (Es) and transpiration (Ev) coupled to a soil water balance model for improved rainwater productivity. Therefore, the aims of the study were:

- to quantify the soil water balance components for each surface treatment using the measured rainfall and soil water content; and empirically calculated runoff, run-on and soil water evaporation, therefore being able to calculate the transpiration as a residual; and
- to compare the efficiencies of use and storage of rainfall and productivity of the IRWH system to produce maize grain.

7.2 Materials and methods

7.2.1 Experimental layout

For the experiment 2008/09, all the RSL treatments and five sub-plots of the ML treatments, *viz*. Bare (0%), 1 t ha^{-1} (12%), 2 t ha^{-1} (39%), 3 t ha^{-1} (64%) and 5 t ha^{-1} (96%) each replicated three times were used for the water balance and water productivity studies. Furthermore, for bare plots of all RSL treatments, the grain seed yield and biological yield (AGDM) values were used to compare the two growing seasons (2007/08 and 2008/09). Mulch was only applied as a sub-plot in the second cropping season (2008/09). Detailed description of the site, climatic conditions of the cropping season and crop management aspects were described in Chapter 2, Section 2.1 – 2.4.

7.2.2 Experimental approach and measurements

7.2.2.1 Soil water balance components

A simple form of water balance quantification appropriate for IRWH in arid and semi-arid areas has been adopted from Hillel (l982). Evapotranspiration (ET=Ev+Es) can be estimated with the water balance equation for dryland crop production in soils without a watertable and without significant internal lateral water movement and can be written as follows (Bennie *et al.*, 1994):

$$Water\ for\ yield = water\ gains - water\ losses$$

$$Ev = (P \pm \Delta S) - (Ro + Es + D) \qquad \textbf{7.1}$$

The equation is stated as general concept that water for yield is equal to the water gains minus water losses. In this model, a portion of rainfall (P) infiltrates into the soil and becomes available for root extraction together with the change in soil water content (ΔS) between the beginning and end period. The losses include the amount of water evaporated from the soil surface (Es), the surface net runoff (Ro) and the drainage amount (D). Ev represents the crop transpiration which is part of the total evapotranspiration. However, the IRWH technique has two different sections in each field, the basin (BA) and runoff area (RA), that are practically linked as the runoff strip feeds water into the basins. Therefore the water balance components needed are as follows:

- For the runoff area (RA):

$$ET = P - R_{off} - D \pm \Delta S \qquad \textbf{7.2}$$

- For the basin area (BA):

$$ET = P + R_{on} - RCI - D \pm \Delta S \qquad \textbf{7.3}$$

where R_{off} and R_{on} represent runoff from the runoff strip and run-on into the basin area and RCI is the rainfall canopy interception (details in Chapter 4). The units for all the water balance parameters are in mm of water for selected time period.

The most crucial parameter to determine is how much additional water for productivity is added to the profile for each runoff strip length. This can be simply expressed by the fraction of water that is available to infiltrate as a fraction of precipitation (FI) in the basin area (I_{BA}) to the amount of precipitation ($FI = I_{BA}/P$).

The water balance model described in this study, analyzes the relationship between water added to the soil in the basin, where the crop grows, from precipitation and in-field run-on (R_{on}) and the water lost through evaporation and deep percolation. In the analysis, the parameter RCI, used in the basin and runoff area, refers to the amount rainfall intercepted by the crop canopy and then directly evaporated, i.e. rain that never reaches the soil surface. Hence, the amount of precipitation entering the soil profile is the so called infiltration. The procedure used to calculate the run-on for different surface treatments was described in Chapter 4, Section 4.2.3.

i) Drained upper and lower limit of available water

Deep drainage is one of the water losses in the process of water balance calculations. The magnitude of water holding capacity of the root zone is determined by the drained upper limit of plant available water (DUL). The DUL of the soil is the highest field measured water content of each soil layer after it has been thoroughly wetted and allowed to drain until drainage becomes practically negligible. Ratliff *et al. (*1983) stated that a DUL of the particular soil can exist, when the water content in profile decreased by less than 0.1- 0.2% per day. DUL at the Kenilworth Bainsvlei ecotope was used from a recent M.Sc. study (Chimungu, 2009), where field and laboratory measurements of selected diagnostic soil horizon were compared. The *in situ* determination of DUL was used in the water balance calculations for this study. Ritchie (1981) and Ratliff *et al.* (1983) as cited in Chimungu (2009) suggested that due to the accuracy of laboratory methods, the field estimated DUL should be used with caution. However, Romano (2002) claimed that field measurements were preferable for soil water balance calculations, accentuating the importance of a field determined DUL.

The lower limit of the plant available water (LL) is the lowest field measured water content of a soil after plants have stopped extracting water at or near premature death or when dormant as a result of water stress (Ratliff *et al.,* 1983). The LL was determined during the course of a growing season by taking the lowest water content measured for each soil layer for separate basin and runoff areas. The value of LL could vary according to different seasons and is highly related to soil water - crop relationships for a particular ecotope (Ratliff *et al.,* 1983; Hensley *et al.,* 1997; Hensley *et al.,* 2000). Plant available water capacity (PAWC) in the root zone can be estimated by simply subtracting the LL values from the DUL values (Hensley *et al.,* 2000), *viz.*

$$PAWC = DUL - LL \qquad \textbf{7.4}$$

where DUL and LL are upper and lower limits of the plant available water, all in mm.

Furthermore, under field crop conditions the DUL is affected by the root extraction rate. Hattingh (1993) and Hensley *et al*. (1993) developed a concept for maximum amount of available water extracted from the root zone for a particular growth stage and particular evaporative demand.

ii) Soil water content

To monitor the soil water content of the root zone (SWC) neutron water meter access tubes were inserted to a depth of 1800 mm, which is deeper than the expected root zone. In the cropping season 2007/08 (first cropping season) and during the fallow period in 2008 access tubes were located in the centre of the basin and runoff area of each plot. While in cropping season 2008/09 (second growing season) additional tubes were located in each one meter section of the runoff strip. Thus, primarily the change in soil water content was calculated for each 1m section of the runoff area and at the centre of the basin area. Secondarily, the mean of the change of soil water over the basin and each 1 m section of the runoff area were taken to calculate the residual ET values for the whole system of IRWH.

The water content readings were not performed on regular basis but mostly the readings were at an interval of 1-2 weeks except at a time when the neutron water meter had a problem and taken for repair. Additional readings were performed during some periods after rain days and after long dry spells. Nonetheless, the main challenge of the measurements of soil water content were the high variations of the reading taken in particular for measurements in the two top layers of the soil profile. Subsequently, the adjacent access tubes installed on each treatment gave more accurate soil water status for each section of runoff and basin area, but require continuous calibration of the neutron water meter equipment. However, for this study the field measured soil water content readings were utilized by applying the calibration regression equations formulated from the previous study of the experimental site (see Chapter 2, Section 2.4.2.1).

7.2.2.2 Crop parameters and grain yield

Out of the four row planting strips allocated to each treatment, the two middle rows (2^{nd} and 3^{rd} row planting strips) were selected for sampling of crop growth, biomass and yield measurements. Samples were taken for each plot from both rows from the ridge and basin sides. Plant densities were assessed after emergence and again after full cover on 10 meter length along a row for each plot.

The dry matter was measured periodically from 25 days after planting until the plant attained maximum size (65-70 DAP). During sampling, the height of each plant was recorded and cut at the soil surface and then separate into green and dead leaves, stems and reproductive organs. In the beginning, three plants were harvested (above ground section only) from each replication but in later growth stages only two plants were taken from each basin and ridge side. To determine the harvested biomass, samples were dried in an oven regulated at 70^{o}C for 72 hrs. Thus, the above ground biomass (AGDM), partitioned into leaf, stem and reproductive organs, was calculated as oven dry material in kg ha^{-1}

Grain yield of the maize crop was determined from quadrant samples by harvesting 4 m along rows from each basin and ridge side at the end of the season on each replication. The grain was shelled and weighed oven-dried and adjusted to 12.5% seed moisture content and expressed as kg ha^{-1}. Harvest index (HI) was calculated as the ratio of grain seed yield to above ground dry matter production (Bennie *et al.*, 1998):

$$HI_{AGDM} = Y_g / Y_{AGDM} \qquad \textbf{7.5}$$

where HI_{AGDM} is the harvest index for above ground dry matter, HI_{TDM} is the harvest index for total dry matter, Y_g is the grain seed yield, Y_{AGDM} is the total above ground biomass (kg ha^{-1}).

7.2.2.3 Rainwater use efficiency and productivity

***Rainfall storage efficiency (RSE)*:** Conservation tillage techniques such as IRWH, deal with the water conserved during the fallow period as well as the rainwater received during the growing season. This is because the amount of water stored during the fallow period can be crucial to enhance crop production in semi-arid areas. For the fallow period the RSE equation of Mathews and Army (1960) is relevant, as follows:

$$RSE = \frac{\theta_{p(n)} - \theta_{h(n-1)}}{P_f} \times 100\% \qquad \textbf{7.6}$$

where $\theta_{p(n)}$ is the root zone water content at planting of the current crop (mm), $\theta_{h(n-1)}$ is the root zone water content at harvesting of the previous crop (mm) and P_f is the rainfall during the fallow period (mm).

Precipitation use efficiency (***PUE_{fg}***)**:** For the growing and previous fallow periods together, PUE_{gf} was determined as an acceptable and simple way to describe the efficient use of rainwater available for dryland crop production as given by Hensley *et al.* (2000), *viz*:

$$PUE_{fg} = Y_g/(P_g + P_f) \quad (\text{kg ha}^{-1}\ \text{mm}^{-1}) \quad \textbf{7.7}$$

where P_f and P_g are the precipitation during fallow period and growing season.

***Water use efficiency (WUE_{ET})*:** Water use efficiency was used to measure the efficiency with which a particular crop can convert the water available during the growing season (Hillel, 1972; Tanner and Sinclair, 1983; Botha *et al.*, 2001; Botha *et al.*, 2003). Thus, WUE_{ET} was determined with a slightly modified version of Hillel (1972), Passioura (1983) and Tanner and Sinclair (1983) as follows:

$$WUE_{ET} = Y_g/ET \quad (\text{kg ha}^{-1}\ \text{mm}^{-1}) \quad \textbf{7.8}$$

where WUE_{ET} is water use efficiency in terms of total evapotranspiration (ET) in mm.

***Water productivity (WP_{Ev})*:** Water productivity was determined with an approach used by Passioura (2006) as productivity is a function of transpiration lost from the crop. WP_{Ev} therefore, measures the efficiency with which a particular crop can convert the water used by the plant as transpiration into grain yield during a particular growing season:

$$WP_{Ev} = Y_g/Ev \quad (\text{kg ha}^{-1}\ \text{mm}^{-1}) \quad \textbf{7.9}$$

where WP_{Ev} is water productivity and Ev is crop transpiration in mm.

Therefore, based on these simple principles of water balance and crop productivity one can evaluate which IRWH system produces the highest yield per unit area per available amount of water in order to represent the best practice.

7.2.3 Statistical analysis

In the experiment a Randomized Complete Block Design (RCBD) with three replications was adopted. Thus, from the field measurements a statistical analysis was done on soil water content (SWC) and derivatives of plant available water (PAWC), evapotranspiration (ET), soil evaporation (Es) and transpiration (Ev) values to determine the effect of RSL and ML treatments, using the statistical software SAS 9.1.3 for Windows (SAS Inst. Inc., 2006). Means and LSD test for the main treatment effects were computed based on the variability associated with the type of measurements. Test for significance levels of $P \leq 0.05$ and $P \leq 0.0001$ were used. The same statistical procedure was applied to crop parameters and efficiencies (such as Y_g, AGDM, HI and all water use efficiency parameters) across the various surface treatments (RSL and ML). Empirical relationships of the parameters were also derived using regression procedures.

7.3 Results and discussion

7.3.1 Drainage and soil water extraction management levels

The drainage curve for the whole root zone (1800 mm) provides the information for determining the DUL value for the experimental site (Fig. 7.1). The plant available water capacity of the root zone is calculated from the difference between drained upper limit of plant available water (DUL) value of 475 mm and the maize crop lower limit (LL). Due to the fine sandy loam soil texture and increasing clay content with depth down the profile, the soil is expected to reach a maximum water holding value within the 600 - 900 mm layer. The high clay content below 900 mm reduces deep percolation, so drainage losses are considered to be negligible throughout this study.

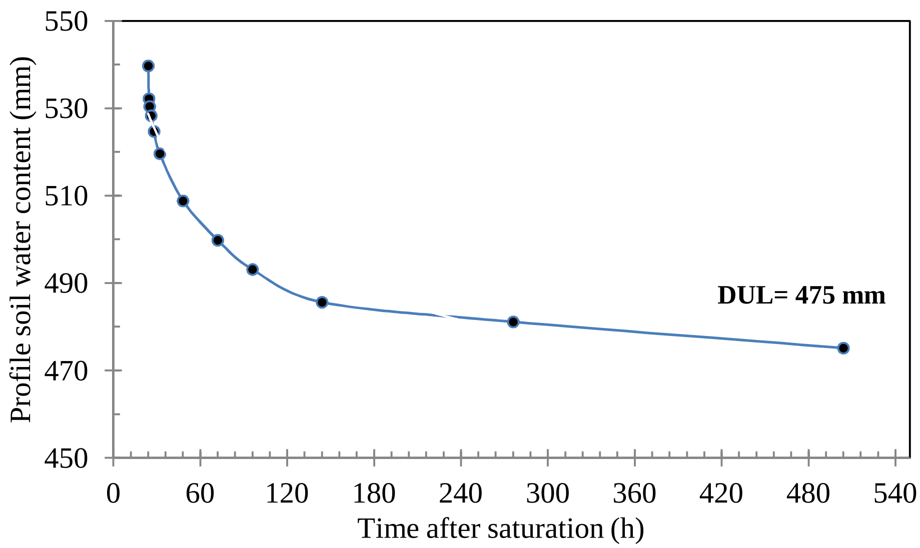


Figure 7.1 Drainage curve for the Kenilworth Bainsvlei ecotope for the root zone 0-1800 mm determined from field data of Chumungu (2009) and personal communication with Malcolm Hensley in September 2010.

The polynomial fitted line for determining DUL is as follows:

$$SWC = 528.75 - 20.53(ln\,(t)) \qquad R^2 = 0.92 \qquad \textbf{7.10}$$

where SWC is the soil water content of root zone of 0 - 1800 mm soil profile and t is time (in hours) after drainage starts from the root zone water content of field saturation.

Equation 7.10 would be used to calculate drainage (D) of the root zone if heavy rainstorms occur for the IRWH experimental site on that specific Kenilworth Bainsvillie ecotope. This can be necessary to quantify the drainage term in the water balance (Eqs. 7.2 and 7.3). The crop lower limit (LL) of extractable water for the runoff and basin area was determined over the profile depth of 1800 mm (Table 7.1). The total extractable soil water (PAWC) was 222.0 mm and 248.5 mm for the runoff and basin area, respectively. This is 10.7% higher in the basin area compared to the runoff area. This was probably possible as a result of the potentially higher root ramification in that part of the soil profile in the planting zone of the basin area. Moreover, the basin area is a water collecting zone due to the run-on processes; and so it makes additional water available in the root zone for extraction. However, the amount of extractable water actually available may vary according to surface treatments, i.e. the length of runoff strips and mulch cover levels.

Table 7.1 Soil profile components of the Kenilworth Bainsvlei form soil (Amalia family) at the experimental plot. The effective root zone for maize is considered 1800 mm (Hensley *et al.*, 2000).

Horizon[1]	Clay %	BD[2] (Mg m^{-3})	Depth (mm)	DUL (mm)	LL for RA (mm)	LL for BA (mm)	PAWC[3] (mm)	
							RA	BA
A	8.5	1.28	300	68.4	12.1	10.4	56.3	57.5
B1- B2	9.5	1.40	600	72.8	47.4	34.1	25.4	38.7
B2- B3	14	1.66	900	80.3	51.2	45.7	29.1	34.6
B3	14	1.67	1200	84.6	49.5	46.6	35.1	38.0
B4	24	1.68	1500	84.6	46.3	46.1	38.3	38.5
B5	24	1.67	1800	84.6	46.8	43.9	37.8	40.7
Total				475.3	253.3	226.8	222.0	248.5

[1] Horizon soil depth classification A (0- 250 mm), B1 (250- 420), B2 (420-700), B3 (700-1200), B4 (1200-1450) and B5 (1450-1850), [2]BD=Bulk density and [3]PAWC= plant available water capacity (The soil physical characteristics for the profile were presented as cited by Chimungu, 2009).

7.3.2 Water balance components

The water balance processes identified in Eqs. 7.2 and 7.3 for runoff and basin areas are relevant in the functioning, productivity and in explaining the soil-plant-atmosphere continuum (SPAC) under the IRWH techniques. Thus, it is important to monitor these processes through field measurements and estimations of water balance components in order to obtain a good understanding of improved crop productivity for IRWH system.

7.3.2.1 In-field runoff and infiltration

In-field runoff processes are considered as one of the most important parameters in the technique of IRWH. The in-field runoff processes have been discussed in detail in Chapter 3 and 4, in which runoff was characterized according to the ratio of basin to the runoff area. It is estimated as the amount that infiltrates as a fraction of precipitation for a growing season (FI). From the result in Chapter 4 therefore, it was shown that different lengths of runoff with a range of mulch levels had an influence on the runoff–rainfall relationships. In order to make a quantitative redistribution of the amount of rainwater that can be infiltrated into the soil for crop productivity the basin area values (I_{BA}) were taken as the fraction of the amount of precipitation($FI = I_{BA}/P$). Figure 7.2 shows the relationship between the infiltrated fraction of rainwater and mulch levels for different RSL treatments.

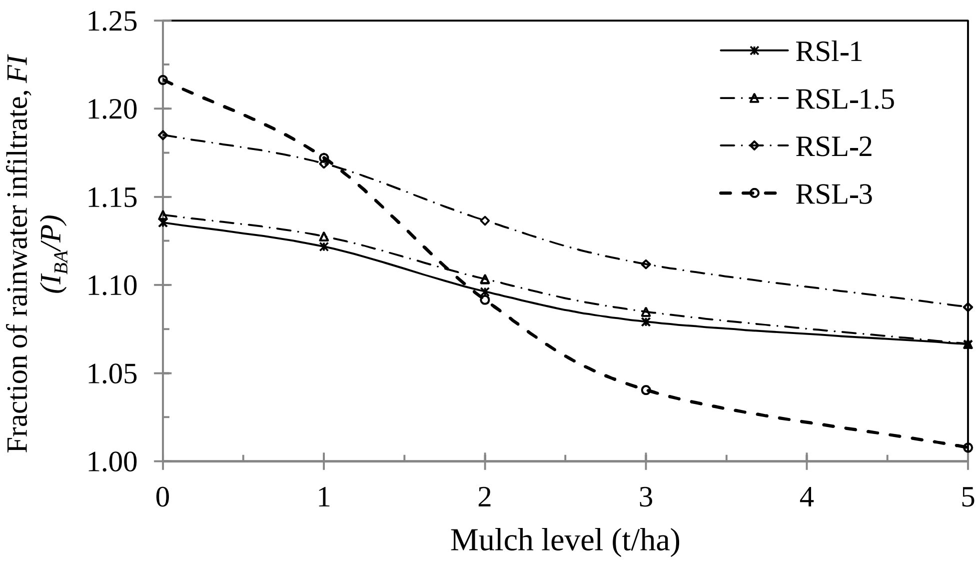


Figure 7.2 Relationship between the rainwater that was available to infiltrate as a fraction of basin precipitation ($FI= I_{BA}/P$) and mulch rate applications for different runoff strip lengths.

With an increase in mulch cover level, the fraction of infiltrated water in the basin area reached a higher value only on two meter long runoff (RSL-2) compared to other RSLs. This implies that more runoff occurred from where there was insufficient mulch cover on the runoff sections, and a high infiltration occurred from bare and two meter long runoff strip. On the other hand, higher infiltration on the runoff area also occurred in the wide RSL-3 and with an increase in mulch levels. RSL-3 treatments with minimum mulch cover (MR0% and MR12%) recorded higher infiltration but showed values less than the RSL-1 and RSL1.5 with an increase of mulch level cover. Conversely, the full mulch cover of RSL-1 and RSL-1.5 were shown to have higher infiltration than the wide RSL-3 treatments. Surface redistribution of the rainwater in the system of IRWH is one of the main processes influencing the water regime of the root zone and hence the yield. During the cropping season 2008/09 the values of infiltration ratios for basin to runoff area

(I_{BA}:I_{RA}) and FI were calculated for the four lengths of runoff strip and each with five levels of mulch cover for different growth stages for the water balance sheet calculations (Appendix 7.1-7.5). These results exclude the amount of rainfall canopy interception (RCI) during each growing period (Chapter 4, Section 4.3.1). Then, these results were used as input into the water balance for this study in order to calculate ET as a residual.

7.3.2.2 Seasonal soil water content

Soil water content at planting and harvesting

The soil water content for the root zone (0 - 1800 mm) at planting (SWC_{pl}) and at the end of the growing season (harvest) (SWC_{hr}), and for the previous year at harvest (SWC_{pc}) show variations but did not follow regular patterns according to longer runoff strip or higher mulch levels (Table 7.2).The statistical analysis indicates that the mulch treatments did not significantly affect the mean SWC_{pl} at any RSL treatments (Table 7.2), which is good as this was the beginning of the experiment when mulch was applied. However, there was significant difference between RSL treatments for mean SWC_{pl} with significantly higher value (394 mm) for narrow RSL-1 and 1.5 compared to wide RSL-3 treatment. The mean SWC_{hr} showed significant difference ($P \leq 0.05$) for both RSL and ML treatments. This showed the mean SWC_{hr} in RSL-2 ML64% was significantly higher than ML96% for 64% mulch cover with LSD value of 19.1 mm and 12.5 mm for RSL and ML treatments, respectively, however there were no significant differences between the remaining RSL treatments (Table 7.2). Only the bare plot SWC measurement, on the RSL treatments varied at the previous harvest time, SWC_{pc} with higher value on RSL-2 (360.8 mm) than the rest of the RSL treatments. These variations in SWC_{pl}, SWC_{hr} and SWC_{pc} help to improve one's understanding of the critical water regimes across the season. Thus, conserving rainwater during fallow and growing periods is essential to improve productivity. Furthermore, monitoring of the change in soil water content during the growing period is an important feature to illustrate the critical stages and water management borders that relate to various positions on the IRWH treatments. The changes in water content (ΔS) for each growth stage at different positions for all treatments were given in Appendix 7.1-7.5.

Table 7.2 Water content for the root zone (0 -1.800 mm) in the profile on different runoff lengths with different mulch levels, SWC_{pc} (water content at previous year harvest, May 2008), SWC_{pl} (water content at planting, Dec 2008) and SWC_{hr} (water content at harvest, May 2009).

RSL treatments	SWC (mm)	Mulch level (ML) (t ha^{-1})					
		0% (Bare)	1 (12%)	2 (39%)	3 (64%)	5 (96%)	**Mean**
1 m	SWC_{pc}	348.2					
	SWC_{pl}	383.5	399.8	396.4	395.1	397.1	394.3a
	SWC_{hr}	341.9	334.6	357.6	364.7	339.9	347.7ab
1.5 m	SWC_{pc}	349.5					
	SWC_{pl}	426.2	365.8	409.3	373.0	396.9	394.3a
	SWC_{hr}	349.9	313.9	347.0	379.4	366.5	351.3ab
2 m	SWC_{pc}	360.8					
	SWC_{pl}	397.8	386.3	369.3	388.4	393.9	387.1ab
	SWC_{hr}	348.2	328.4	373.7	383.2	348.2	356.3a
3 m	SWC_{pc}	343.5					
	SWC_{pl}	378.5	390.5	381.1	382.6	380.4	382.6b
	SWC_{hr}	342.0	317.1	331.6	364.9	352.9	341.7b
Mean	**SWC_{pl}**	396.5	385.6	389.0	384.8	392.1	
	SWC_{hr}	345.5bc	323.5d	352.5b	373.1a	351.9b	
LSD: RSL-SWC_{pl} = 10.1 ML-SWC_{pl} = ns RSL-SWC_{hr} = 12.3mm ML-SWC_{hr} = 19.1 mm							

**Each data point represents an average of three replicates with highly variations at significance level P < 0.0001significance level.*
***ns = none significant; means followed by same letter are not significantly different (P < 0.05)*
****SWC_{pc} measurement was only done on bare treatments before the mulch was applied to the experimental plot.*

Change in soil water content

All the graphs (Fig. 7.3-7.5) incorporate the seasonal rainfall pattern with a total of 249.8 mm rain being received during the cropping season (2008/09). The highest rainfall was on 22 and 39 days after planting with amounts of 24.0 and 25.5 mm respectively. Ten of the rainfall events exceeded 8 mm amounting to 149 mm (59.5%) of the total amount of rainfall during the season. Seven of the rainfall events were 5-8 mm and gave approximately 20% of the total rainfall (as discussed in Chapter 3, Section 3.3.1). The rest of the events were below 5 mm and could have been lost immediately as evaporation from the IRWH plots. For the purpose of describing the variation SWC was categorized according to the shading effect of the basin area and for each 1 m section along the runoff area and discussed according to phenological growth stages. These are: i) Basin area SWC during, ii) Runoff area SWC with full shaded canopy cover (FC-RA) and iii**)** Runoff area SWC with partially and unshaded canopy cover (PC-RA & UC-RA).

i) Basin area SWC (FC-BA)

There were no significant differences in the basin area between RSL-1, 1.5 and 2 treatments, but the wide RSL-3 treatment had a significantly lower soil water content (332 mm) than the others during two periods around 28 DAP and 80-84 DAP. From Fig. 7.3, the basin area showed significantly higher mean soil water content on 34 DAP (410 mm) than other measurement days but the highest SWC was recorded on 29 DAP (433 mm) on RSL-1 treatment. The first 34 days of the cropping season had a significant higher SWC in the basin area across all treatments but only RSL-3 treatment dropped to lower values of 305 mm on 29 DAP, although was recharged soon with the rainfall amount of 16.2 mm on 20 Jan, 2009 (31 DAP). Therefore during the early vegetative period of GS-I, the highest water content in RSL-1 (432.8 mm) was due to the advantage of pre-season water storage in the profile of the basin areas that can compensate for possible poor rainfall at the start of the growing season.

During the late vegetative period, after the highest rainfall event on 38 DAP (25.5 mm), there was a long dryish period for approximately 18 days with only small rain showers. This resulted in a decrease in the SWC in the basin area to about 370 mm on the RSL-1, RSL-1.5 and RSL-3 treatments whereas, RSL-2 treatment dropped by 30 mm being more than other treatments (Fig.7.3). This is possibly an indication of very low rain storage efficiency for RSL-2 treatment, which was only about one-third or less of the other treatments (i.e. RSE of 6.7 - 9.9%), see Section 7.3.4.2, together with the higher plant population and thus deeper roots to extract more soil water. However, in the second growth stage (GS-II) after receiving an a total of 27.7 mm rain between DAP 53 and 56, it caused the root zone SWC in all treatments to rise, though the narrow treatments (RSL-1 and RSL-1.5) showed significantly higher SWC than wide treatments (RSL-2 and RSL-3).

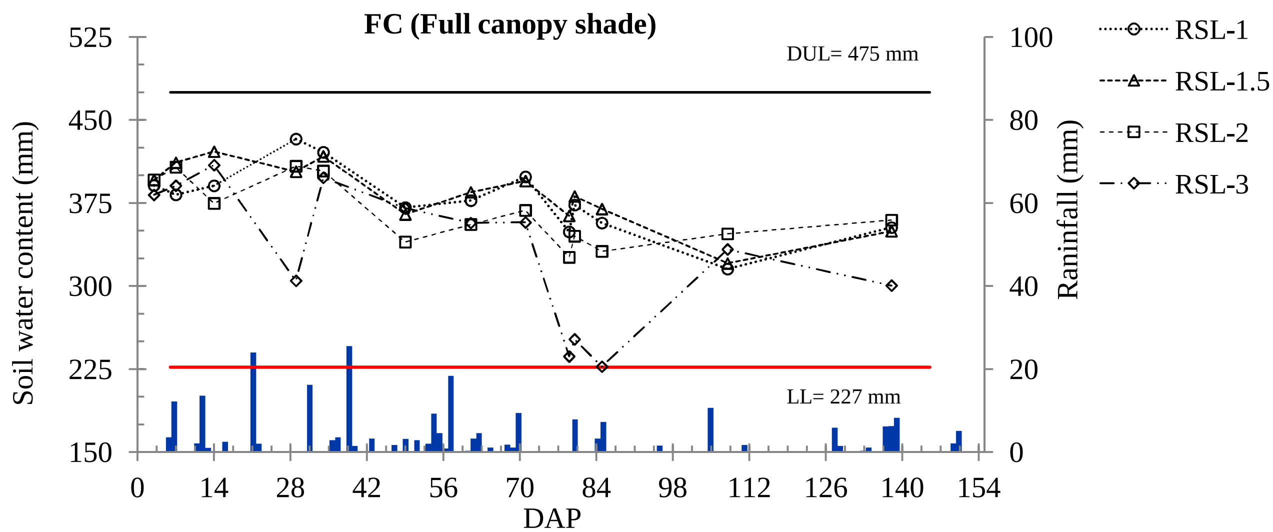


Figure 7.3 Measured changes in soil water content of the root zone (0-1800 mm) in the basin area of different runoff length treatments (RSL) through the 2008/09 cropping season. Daily RF for the season and water management borders *viz.* DUL and LL values are included. Each data point represents the mean of three replicates (n=3).

As is often the case in a semi-arid environment, the rainfall does not come regularly throughout the crop growing season. For example, during GS-III (71-105 DAP) little rainfall was received (Fig.7.3), as a result the SWC of the root zone declined to significantly lower values than during other growth stages. The RSL-2 declined to SWC of 326 mm and RSL-3 SWC dropped nearly to LL during this critical yield formation period 79-85 DAP, which would have a serious effect on the yield. Furthermore, the basin area of RSL-3 treatment declined again after a small rainfall of 10.7 mm on 102 DAP (Fig. 7.3). Therefore, the decline of root zone SWC in RSL-3 basin showed rapid extraction of water during dry periods, but the basins of the narrow treatments total water profile extraction was not different between growth stages.

ii) Runoff area SWC with full shaded canopy cover (FC-RA)

Under IRWH, a higher proportion of the rainwater is expected to be concentrated in basin than in the runoff section. For instance, in Fig. 7.4a and b on the narrow runoff strip (RSL-1 & 1.5) under full canopy shading (FC-RA), no significance differences were measured for different mulch applications on the runoff strips throughout the season.

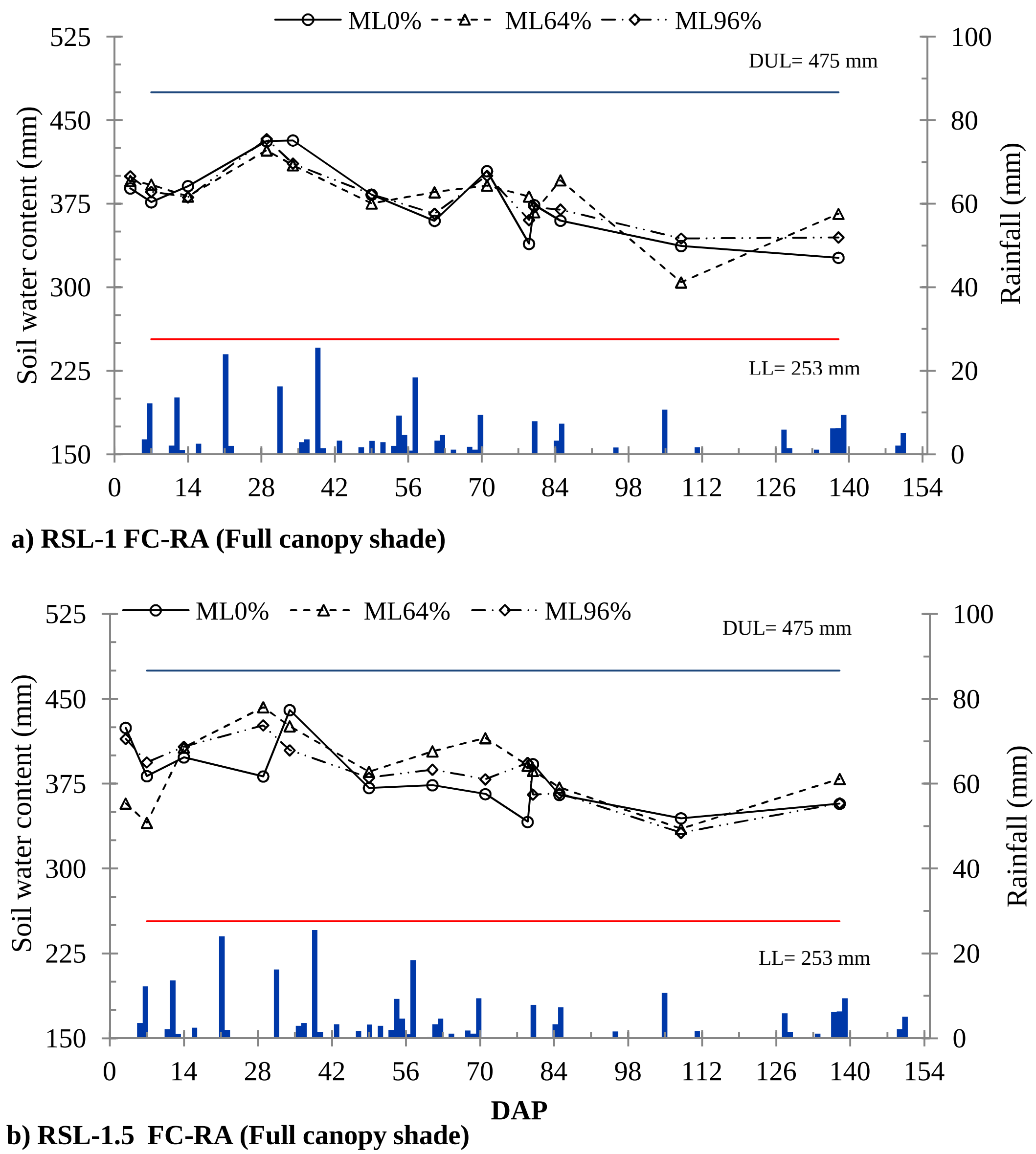


Figure 7.4 Measured changes in soil water content of the root zone (0-1800 mm) in the full canopy cover runoff areas of a) RSL-1, FC-RA and b) RSL-1.5, FC-RA and different mulch levels (ML), for cropping season 2008/09. Daily RF for season and water management borders *viz.* DUL and LL values are included. Each data point represents mean of three replicates (n=3).

The plants roots had equal opportunities to access the available water in both basin and runoff sections of RSL-1 with 1 m runoff length treatments. The water content of all the mulch treatments were relatively constant until the crop reaches full canopy cover (55-65 DAP), when a series of five rain events (44 mm) boost the soil water content. From flowering/tasseling to beginning of yield formation (65-80 DAP), there was a long dry period, so the crops depended heavily on stored water in the profile of the runoff section to maintain the crop water demand, since the water content in the basin area had declined to below 300 mm (Fig. 7.4a). However the SWC on bare runoff plots (RSL-1.5) still remain lower compared to mulched plots during this period of rapid SWC extraction (79 and 85 DAP) during reproductive stage (Fig. 7.4b).

In the case of RSL-1.5, the mulch treatment showed a significant effect with lower SWC during the first half of the season for plots with less mulch, except on 34 DAP when zero mulch treatment had the highest SWC but it was again lowest later (108 and 138 DAP) (Fig.7.4b). Therefore, results revealed that mulch placement and the shading effect on narrow RSL treatments were effective in conserving soil water in the runoff strip profile compared to bare plots though the differences were not statistically significant.

iii) Runoff area SWC with partially and unshaded canopy cover (PC-RA & UC-RA)

Mulching had a significant effect on the total soil water content of partially shaded runoff strips in RSL-2 and RSL-3 treatments. Fig. 7.5a shows that during the growing period, from vegetative to reproductive stage (28-85 DAP) the bare 2 m runoff strips had higher SWC whereas the mulched plots followed the same trend but with lower SWC and declined towards LL during the yield formation period on 79 DAP. The mulched runoff strips with 64% showed higher SWC after recharged with 10.7 mm (102 DAP) while bare and ML96% did not. The possible reason was due to that fact low infiltration into soil profile on fully mulched runoff area and lower run-on into basin areas after relatively long dry periods.

In the case of RSL-3 runoff treatments, the bare plots reached highest SWC during vegetative growth stage (34 DAP) and then SWC declined throughout the growing period with an exception of a rise on 71 DAP, whereas, the mulched treatments were relatively constant until 79 DAP (Fig. 7.5b). However, there is no clear trend in soil water content measurements for RSL-3 treatments except that the bare partially shaded runoff plots had lowest SWC almost throughout the season (Fig.7.5b). For bare RSL-3 treatment, in both partially and unshaded sections of the runoff strip (Fig. 7.5b & c), the levels of soil water during flowering/tasseling (71 DAP) responded to a rainfall event on 68 DAP of 9.4 mm. Conversely, the 64% mulch cover plots responded after rain event of 7.9 mm on 108 DAP, while the bare plots remained constant till the end of the cropping season at SWC level of about 320 mm.

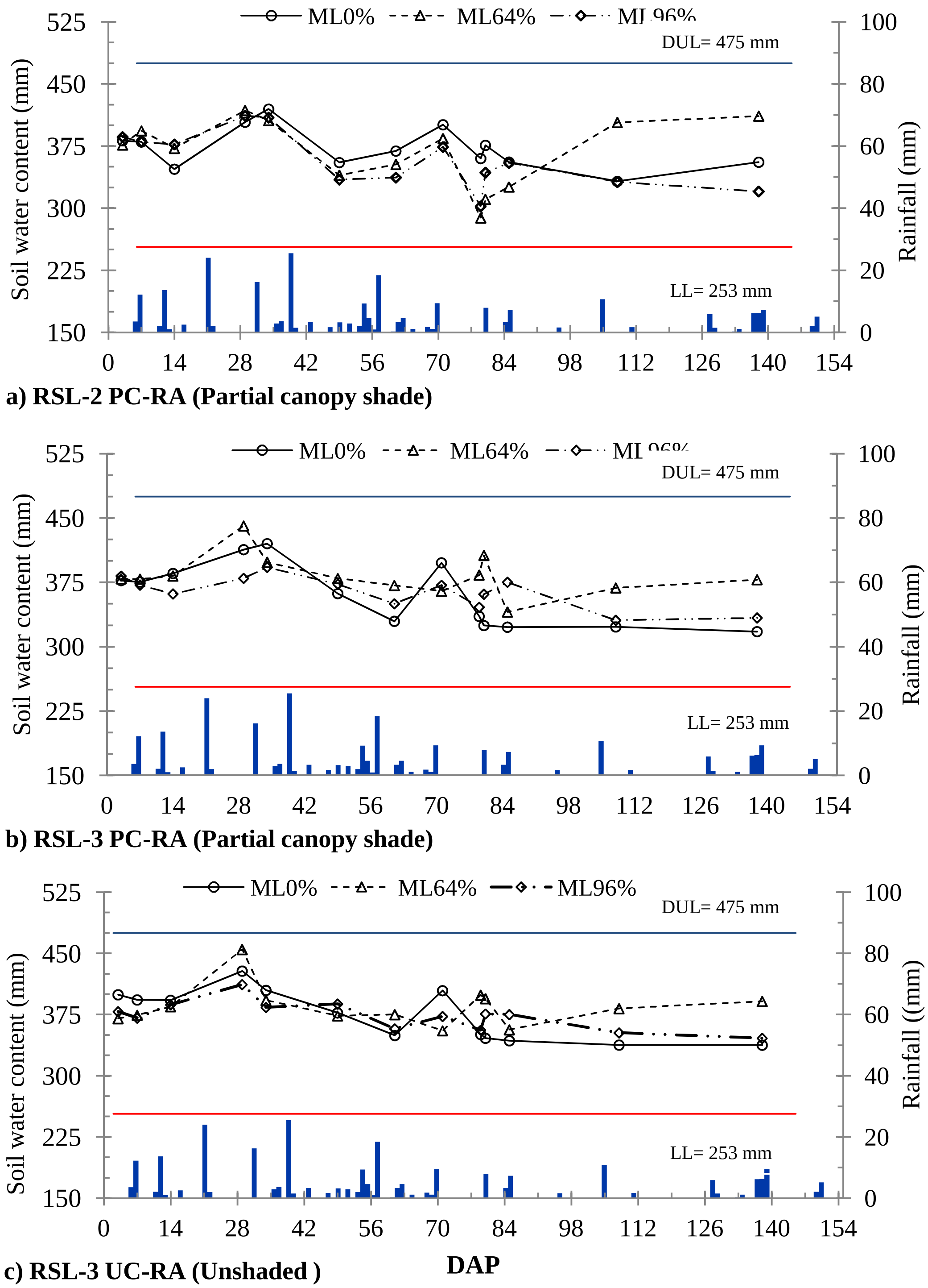


Figure 7.5 Measured changes in root zone soil water content (0-1800 mm) for partial canopy cover and unshaded runoff area a) RSL-2 and b) RSL-3 with different mulch levels for 2008/09 cropping season. Daily RF and. DUL and LL values are shown, (n=3).

In general, these results of SWC runoff areas demonstrated that, both mulch and shading cover were effective in conserving soil water in the runoff strips, but their effect on soil water storage in the basin and on the total soil water content in the profile were not the same for different RSL treatments. In all cases, SWC of treatments and positions in the runoff area decreased gradually from planting towards the reproductive period but then mainly remained constant till the end of the growing season. The wide RSL-3 treatments in the basin area and RSL-2 in the runoff area were close to LL limit, indicating that water stress was present from approximately tasseling time till yield formation period (71-85 DAP). As can be seen from the DUL limit of 475 mm, the SWC in the root zone (0-1800 mm) was never close to that limit where drainage could occur throughout the growing season. So it is concluded that it is safe to neglect the drainage term in the water balance equation (see Section 7.3.1).

7.3.2.3 Evapotranspiration

Evapotranspiration (ET) was estimated as residual using the water balance equation as determined by Eq. 7.2 for runoff area and Eq. 7.3 for basin area. ET was then separated into its components, *viz.* evaporation from the soil surface (Es) and transpiration (Ev). The Es results, as influenced by mulch and canopy shading were determined in detail in Chapter 6 Section 6.3.3 using the newly derived empirical equations (Eqs. 6.2 for basin area and Eq. 6.3 for runoff area). Ev is calculated as difference between ET and Es. These components for the whole cropping season (2008/09) are summarized in Table 7.3 for runoff length treatments (RSL) with different levels of mulching cover. Details of ET, Es and Ev for different growth stages are also presented in Appendix 7.1-7.5. The statistical analysis showed that there were significant differences for the parameters (ET, Es and Ev) caused by the effects of surface treatments (RSL and ML) at $P < 0.05\%$ significance level but, that there was no interactive effect among the surface treatments (Table 7.3).

In the maize field of IRWH under different RSL treatments with various mulch cover, the ET varied between 210 mm and 320 mm during the growing season. Overall, the RSL-1 treatment with low mulch cover (ML12%) used the absolute highest ET. However, the wide RSL-3 and RSL-2 treatments with fully mulch covered runoff (ML96%) gave higher ET values than their respected bare and low mulched (ML0% and ML12%) treatments. Moreover, lower ET from the narrow treatments (RSL-1.5) was obtained at the relatively higher mulch cover (ML64%), but in wide treatments the lower mulch cover produced lower ET compared to fully mulched cover plots. The reason could lie in the effectiveness of the surface treatments in allowing water to penetrate and infiltrate as well as limiting water losses from the soil surface. Thus, all the narrow

RSL-1 fully covered benefitted from the canopy shade on both sides, and the mean ET across mulches was significantly larger than the other RSLs. In contrast, the mulched wide runoff had an advantage in reducing evaporation losses and promoting infiltration into the runoff area. These calculated ET values across treatments for the whole growing season do not show simple linear relationships between RSL and mulch levels as they represent the whole treatment and not a section of it. Therefore it is difficult to logically try to explain the treatment differences without having a more detailed monitoring of a single plot or treatment.

Table 7.3 Seasonal evapotranspiration (*ET*) as partitioned into calculated soil evaporation (*Es*) and transpiration (*Ev*) for different runoff lengths (RSL) at different levels of mulch (ML); on Kenilworth Bainsvlei ecotope for 2008/09 maize season.

	RSL	ML Treatments					
		0 (Bare)	1 (12%)	2 (39%)	3 (64%)	5 (96%)	**Mean**
ET (mm)	1	303.0	319.8	293.9	304.5	302.9	304.8a
	1.5	252.4	254.7	268.7	215.6	232.1	244.7c
	2	252.5	224.1	209.8	229.9	263.1	235.9c
	3	251.1	251.9	281.5	233.6	289.1	261.4b
	Mean	264.7a	262.6a	263.5a	245.9b	271.8a	*LSD*: RSL = 12.4 mm *LSD*: ML = 13.9 mm
Es (mm)	1	153.8	148.9	136.5	125.7	111.6	135.3a
	1.5	138.1	133.1	120.7	110.0	95.9	119.6b
	2	137.8	131.2	114.7	100.3	81.6	113.1c
	3	135.2	127.8	109.2	93.0	71.9	107.4d
	Mean	141.2a	135.2b	120.3c	107.3d	90.3e	*LSD:* RSL = 6.2 mm *LSD*: ML = 3.1 mm
Ev (mm)	1	149.2	171.0	157.5	178.8	191.3	169.5a
	1.5	114.3	121.6	147.9	105.6	136.2	125.1c
	2	114.6	92.9	95.1	129.5	181.5	122.7c
	3	115.8	124.2	172.3	140.6	217.1	154.0b
	Mean	123.4c	127.4c	143.2b	138.6cb	181.5a	*LSD:* RSL = 13.9 mm *LSD:* ML = 15.5 mm
Ev/ET (%)	1	0.49	0.53	0.54	0.59	0.63	0.56a
	1.5	0.45	0.48	0.55	0.49	0.59	0.51b
	2	0.45	0.41	0.45	0.56	0.69	0.52b
	3	0.46	0.49	0.61	0.60	0.75	0.58a
	Mean	0.47c	0.48c	0.54b	0.56b	0.66a	*LSD:* RSL = 0.029 *LSD:* ML = 0.032

Means followed by the same letter are not significantly different ($P < 0.05$)

It is an important measure to manage surface treatments (RSL and ML) for Es reduction under IRWH technique. From the IRWH technique, the Es value was showed to be suppressed by both the mulch and shading effects. Results from Table 7.3 demonstrate that addition of mulch on the runoff area on a sandy loam soil reduced Es losses from a bare by about 5%, 15%, 24% and 35% for the mulch covered plots of ML12%, ML39%, ML64% and ML96%, respectively. This clearly indicates that Es losses were significantly restricted with every increase in mulch cover on the runoff strips. Thus, in all RSL treatments the most restricted Es losses were calculated for the full cover mulched treatments with a mean value of 92.0 mm during the growing season. Thus, the bare treatments showed significantly higher Es values compared to any of the mulched plots. Furthermore, the other factor that reduces Es losses was the shading effect of the canopy. As discussed in Chapter 5 and 6, the wide RSL treatment with high plant densities reduced the Es losses the most. Thus the lowest Es (79.0 mm) was observed from RSL-3 with full mulch cover (ML96%). The narrow runoff with lower plant density had an effect of full canopy shade, but all RSL treatments were significant different, with highest mean Es value of 135.3 mm for RSL-1 and lowest mean Es (108.8 mm) for RSL-3 treatments. Apparently, water conserved by the full mulch cover was available for transpiration which was increased by 65% and conserved more about 21% over bare treatments (Table 7.3).

Unlike the Es, the transpiration (Ev) clearly depends on the plant and available water in the soil. The results of Ev were provided from the ET values by subtracting the estimated Es values for different treatments. This is an opportunity to analyse the effect of surface treatments on the amount of transpiring water for yield generation through the season. The analysis of variance showed that there was a significant difference from both ML and RSL treatments on Ev values (Table 7.3). The highest mean Ev value was observed from fully mulch plots (181.5 mm) and lowest from the bare treatments (123.4 mm) with LSD value of 15.5 mm. Similarly, the narrow RSL-1 treatment showed a significantly higher Ev compared to all other RSL length plots. However, RSL-1.5 and RSL-2 were also significant different and rendered lower Ev values of 125.1 mm and 122.7 mm through the whole growing season than the RSL-3 plot (Table 7.3).

The Ev/ET ratio is an indication of the portion of ET that would be productive in producing the grain yield. The mean Ev/ET value results were significantly higher for both wide RSL-3 (58%) and RSL-1 (56%), than the RSL1.5 and RSL-2 treatments which gave lower Ev/ET values (about 52%) with insignificant differences with LSD value of 2.90% (Table 7.3). With regard to ML treatments, the full mulch resulted in significantly higher Ev/ET with a value of 66% than all other mulches, showing that nearly two thirds of the ET was used for grain production. The lowest Ev/ET was found for bare treatments with a mean value of 47%, indicating that less than half the ET was used for grain production (Table 7.3).

Therefore, it has been shown that IRWH treatments with mulch and shading effect lost a smaller portion of ET to Es compared to bare plots. In other words the mulch applications of IRWH techniques were successful in minimizing the unproductive losses of water through Es. Moreover, the canopy shade cover also played a great role in reducing Es, but it was different for different positions along the runoff section and so it not reflected in this calculation for the whole treatment.

The seasonal detail of Ev, Es and ET across treatments and how they were partitioned into four growth stages is given in Appendix 7.1. The results showed statistically inconsistent over the growth stages for different runoff lengths and mulch cover (Appendix 7.1). The GS-I had significantly higher differences than growth GS-IV but the Es values for GS-II and GS-III were shown to fluctuate for different treatments. However, the soil evaporation Es during GS-I was always shown to be significant higher than the rest of the growth stages, as expected due to the presence of few leaves in the beginning of the season. For a clay soil at the Glen/Bonheim ecotope (47% clay) Botha (2006) reported that Ev/ET values for maize under IRWH was in the range of 37% - 43% with various surface treatments while the conventional tillage gave only 28%. Similarly, Es/ET values were reported as 57% - 63%, i.e. Ev/ET $\ll$ Es/ET. These values were not of the same order as these results for the fine sandy loam soils of this experimental site, where Ev/ET $\gg$ Es/ET for higher mulch covered treatments. However, for bare or lower mulch cover Ev/ET was in the range 41 - 53%. This demonstrates the advantage of surface treatments in minimizing the unproductive losses of water through Es. Therefore, it is suggested that despite lower crust formation on this soil compared to clay soils, the fine sandy loam soils could play a big role in promoting infiltration capacity and in minimizing Es losses, in particular together with mulch treatments. This implies that the Kenilworth Bainsvlei ecotope is suitable for the application of the IRWH technique, as long as it is combined with mulch treatments.

7.3.3 Yield and water productivity

7.3.3.1 Yield response and dry matter accumulation

The comparison of bare plots as affected by RSL treatments for the cropping seasons in terms of grain yield and biomass yield (AGDM) had revealed significant differences ($P < 0.05$) with LSD values of 356 kg ha^{-1} and 652 kg ha^{-1} respectively. The statistical analysis showed that the mean grain yield for maize was higher during the second cropping season but the AGDM was higher during the first cropping season with highest value of 3535.2 kg ha^{-1} and 8091.3 kg ha^{-1}, respectively (Fig. 7.6a and b).

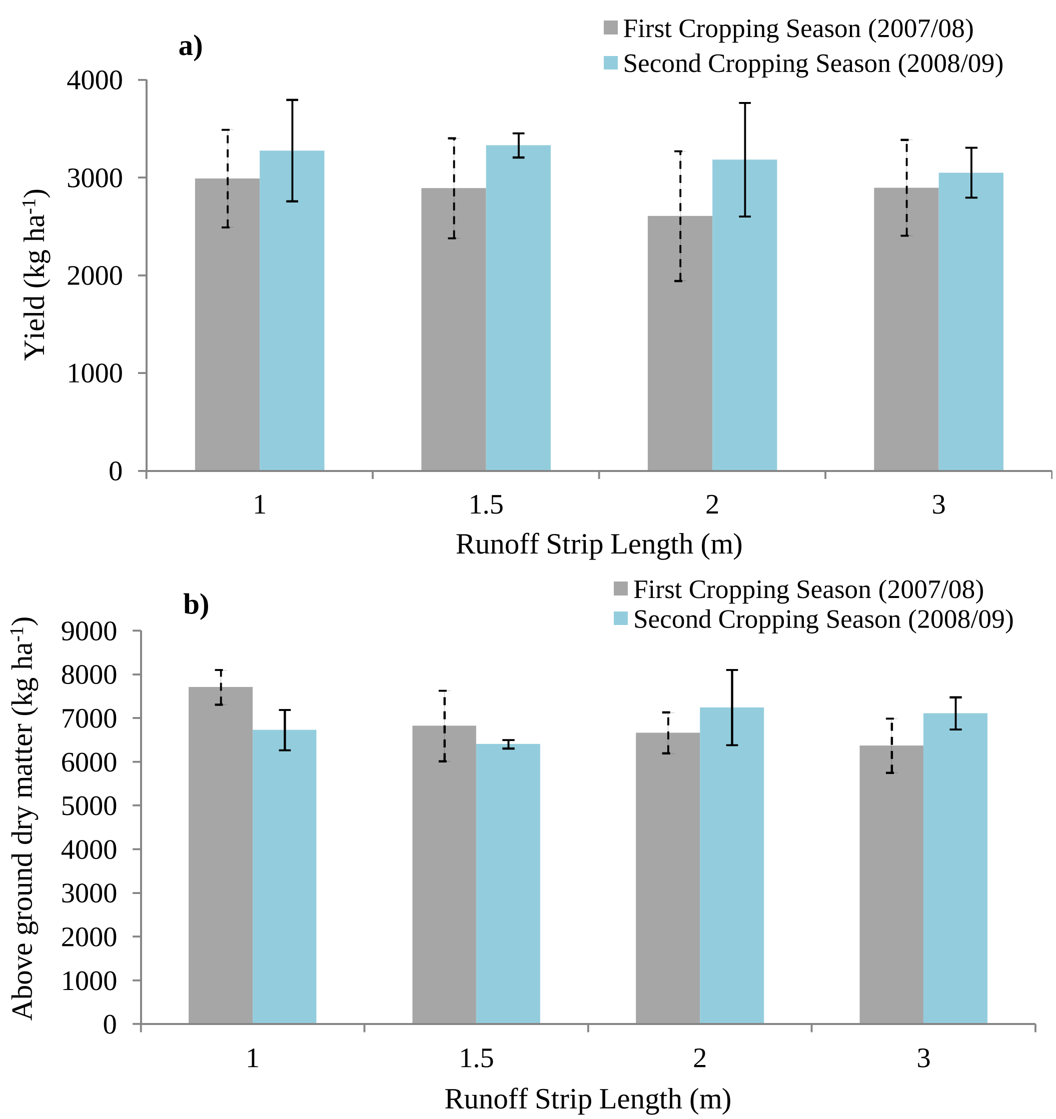


Figure 7.6 Grain seed yield and biomass yield (AGDM) of a maize crop for all RSL treatments during two consecutive cropping seasons (2007/08 and 2008/09) on a bare (un-mulch plots) at Kenilworth Bainsvlei.

The analysis also indicates that the mean yield for RSL-1 was better, then followed by RSL-3 > RSL-1.5 > RSL-2, however there were insignificant variations between all the RSL treatments. On the other hand the AGDM performed significantly better for RSL-1 compared to the rest RSL treatments. Nevertheless the lowest mean biomass yield (AGDM) was observed for RSL-3 treatment with a value of 6767.3 kg ha^{-1}. Therefore, it can be suggested that the first season had more favourable resource availability compared to the second season and this can be seen from the generally higher biomass yield performance. On the contrary, the higher grain yield obtained during the second cropping season was due to effective use of rainwater as the effect of surface treatments.

The final grain yield showed no significant differences for different mulch levels (Table 7.4). However, there was a significant higher seed yield in narrow (RSL-1) than the wide (RSL-3) treatments and the mean values of grain yield decreased very slightly (approximately only less than 1%) in order of increasing RSL *viz.* 1, 1.5, 2 and 3 m runoff lengths (Table 7.4). Biomass means varied between 5668.7 kg ha^{-1} and 7290.3 kg ha^{-1} for above ground dry matter (AGDM). The statistical results of AGDM revealed that a significant difference according to the effect of RSL treatments (P value $\leq$ 0.05) with LSD values of 569.1 kg ha^{-1} and 673.3 kg ha^{-1}, respectively but, mulch levels did not statistically influence either biomass parameters. Similar to seed yields, the narrow RSL-1 gave significant higher AGDM compared to the wide 3 m runoff length treatment, while the 1.5 and 2 m runoff lengths showed no significant variations. Evidently, AGDM followed an order of increasing RSL-1>> RSL-2>RSL-1.5 > RSL-3. The harvest index (HI) varied between 0.45 and 0.50 for AGDM across the different treatments, however, HI appeared not to be so sensitive to treatments, and did not show any consistent pattern or order of increasing or decreasing values and had no significant differences between the treatments.

Table 7.4 Grain seed yield, biomass and Harvest Index (HI) for a maize crop under IRWH with different runoff lengths and mulch applications during growing season 2008/09 at Kenilworth Bainsvlei.

Crop parameter	Runoff length (RSL)	Mulch treatments (ML%)					**Mean**
		0%	12%	39%	64%	96%	
Seed (kg ha^{-1})	1 m	3277.5	3359.4	3304.6	3102.3	3157.8	3240.3a
	1.5 m	3184.8	2924.8	2951.3	3108.9	3142.6	3062.5ab
	2 m	3096.7	3100.0	3024.2	2998.4	2915.2	3026.9ab
	3 m	3051.4	2740.6	3051.6	2939.2	2666.2	2889.8b
	Mean	3152.6	3031.2	3082.9	3037.2	2970.5	*LSD:* RSL = 216.8
AGDM (kg ha^{-1})	1 m	7147.6	7290.2	6886.3	6498.4	6794.2	6923.3a
	1.5 m	6516.3	6096.7	6265.9	6466.8	6428.1	6354.8ab
	2 m	6506.6	6476.8	6477.9	6479.9	6327.9	6453.8ab
	3 m	6580.4	6071.4	6121.6	6316.5	5668.7	6151.7b
	Mean	6687.7	6483.8	6437.9	6440.4	6304.7	*LSD:* RSL = 596.1
HI (AGDM)	1 m	0.46	0.46	0.49	0.48	0.47	0.47a
	1.5 m	0.49	0.48	0.47	0.48	0.49	0.48a
	2 m	0.48	0.48	0.47	0.46	0.45	0.47a
	3 m	0.46	0.45	0.50	0.46	0.47	0.47a
	Mean	0.47	0.47	0.48	0.47	0.47	-

AGDM = above ground dry matter. Means followed by the same letter are not significantly different ($P < 0.05$)

The pattern of biomass yields showed the same trend as the grain seed yields. However, the variation is slight for both grain seed and biomass yields. The main possible reason for the results having small variations could be due to the fact that more water for yield was harvested from bare plots than mulch cover treatments, so more soil water was available. But the higher mulch cover conserves much more water by suppressing Es compared to bare treatments, so that the treatments compensate to each other. Moreover, from the runoff results (Chapter 4, Sections 4.3.2 and 4.3.3) more water was collected / harvested from 2 m wide RSL compared to other RSL treatments with various mulch cover. These processes of: i) runoff-rainfall and ii) Es-reduction for various mulch applications and different lengths of the runoff, tends to "narrow the variations" across the treatments as they work against each other or compensate for each other. Thus, a comparison in terms of water or precipitation use efficiency and/or the rainwater use productivity is crucial for evaluating the variations in the IRWH technique in semi-arid area.

7.3.3.2 Use of efficient rainwater for yield

Comparison of results of rainwater use efficiencies (RSE%, PUE_{fg} and WUE_{ET}) for maize crop under IRWH as affected by surface treatments (RSL and ML cover) are presented in Table 7.5 and 7.6.

i) Rain storage efficiency (RSE%)

Mulch application was done at the end of the fallow period (Dec 2008), one week before sowing, so that no data is available for RSE under different mulches. However, there is a large variation in RSE values between RSL treatments, which reflect the influence of runoff and infiltration ratios for various runoff lengths in the basin and runoff area (Table 7.5). For the purpose of the analysis the sub-plots allocated for mulch levels were considered as replications for the bare treatments. This can be attributed to illustrate the effect of crop's ability to extract water from the root zone from the bare treatment during the fallow period. Besides, the water consumed by the previous cropping season also affects the RSE value by contributing to the current cropping season. The corresponding mean RSE in the runoff area, RA (8.0% - 13.7%) was smaller compared to the basin area, BA (13.9% - 17.3%) in general to store water and to be efficiently used during the growing season. There was also a significant difference ($P < 0.05$) of RSE values for the basin and runoff area. The RSL-1.5 treatment induced higher RSE values (19.3) in the runoff area compared to the rest treatments and lowest mean RSL value was observed in the RSL-2 treatment with mean value of about 6.0%, but the small amount of water stored on runoff of RSL-2 treatment during the fallow period (4.4 - 7.1%) compared to other treatments is difficult to explain. Nevertheless, the basin area of RSL-2 treatments stored about the same range of the other treatments (7.3% - 19.4%). Results obtained from RSE analysis indicating that significant variation of the stored water during fallow period occurred in the runoff area but the there was little or insignificant variations in the basin area between RSL treatments and all sub-plots. In addition to the RSE, other forms of water use efficiency (PUE_{fg} and WUE_{ET}) for maize under IRWH were also calculated.

Table 7.5 Different rain storage efficiencies for maize under IRWH as affected by different runoff lengths during the fallow period prior to 2008/09 season for basin (BA) and runoff (RA) area.

Indicator	Treatment (RSL)	Section	Replications allocated for mulch level cover					**Mean**
			1	2	3	4	5	
RSE (%)	1 m	BA	10.9	17.4	15.6	16.8	16.9	15.5[a]
		RA	7.5	12.8	12.2	10.0	11.5	10.8b
	1.5 m	BA	28.6	13.1	17.7	14.1	10.8	16.9[a]
		RA	28.0	10.4	26.5	7.3	24.4	19.3a
	2 m	BA	19.4	11.5	7.3	14.4	14.9	13.5[a]
		RA	4.9	4.4	7.1	6.6	6.5	5.9b
	3 m	BA	10.5	15.4	15.0	16.6	13.2	14.1[a]
		RA	11.4	15.2	8.8	8.3	10.1	10.8b
	Mean	BA	17.3[a]	14.3[a]	13.9[a]	15.5[a]	13.9[a]	LSD: RSL (RA) = 7.3
		RA	12.9a	10.7ab	13.7a	8.0b	13.1a	LSD: ML (RA) = 4.1

Means followed by the same letter are not significantly different ($P < 0.05$). The superscript letters are indicated for the basin area (BA) significant analysis levels.

ii) Precipitation use efficiency (PUE_{fg})

Precipitation use efficiency (PUE_{fg}) was calculated in terms of the use of rainwater through the fallow and growing period together. This is the most comprehensive and important efficiency that makes use of the water losses by intensive soil water measurements. There were significant differences for the treatment effects of RSL and ML cover on PUE_{fg}, with LSD values of 0.026 and 0.023, respectively. The PUE_{fg} of different runoff lengths with various mulch applications varied between 4.8 and 6.2 kg ha^{-1} mm^{-1}. However, the statistical highest PUE_{fg} value was found in narrow RSL-1.5 treatment and followed the RSL-1, although RSL-2 was greater than the wide RSL-3 treatment. The trend showed variations for different mulch cover on the runoff strip with ML64% cover only slightly better than the lowest PUE_{fg} values for ML12% treatment but significantly different according to the statistics. The PUE_{fg} results indicate that the narrow RSL treatments were better at converting rainwater into maize grain compared to wide RSL but the mulch effect did not show a consistent trend, though there was a significant variation between different mulch levels. The possible reason for low and irregular variations in PUE_{fg} is due to primarily to the variation in pre-seasonal advantage of RSE from the fallow period, secondly there was little or no dependence of grain yield on mulch level effects. Moreover, there were opposite advantages of in-field runoff for bare and low mulch plots versus the reduction of soil water evaporation and enhancement of infiltration on wide and fully mulch covered plots.

iii) Water use efficiency (WUE_{ET})

The consideration of evapotranspiration in evaluating rainwater efficiencies may be able to show an advantage in practicing IRWH techniques for semi-arid climatic conditions. WUE_{ET} was calculated using the residual ET from the water balance calculations from planting (Dec 2008) until harvest (May 2009). The results indicate that the WUE_{ET} varied between 9.1 and 15.4 kg ha^{-1} mm^{-1} during the 2008/09 growing season for different RSL and ML treatments (Table 7.6).

Table 7.6 Different precipitation and water use efficiencies for maize under IRWH as affected by different runoff lengths and mulch cover during the 2008/09growth period.

Indicators	Treatment (RSL)	Mulch level treatments (ML%)					
		0%	12%	39%	64%	96%	**Mean**
PUE_{fg} (kg ha^{-1} mm^{-1})	1 m	5.9	6.1	6.0	5.7	5.8	6.00b
	1.5 m	6.0	5.7	6.0	6.2	6.1	6.10a
	2 m	5.6	5.2	5.3	5.6	5.7	5.56c
	3 m	5.3	4.8	5.6	5.5	5.1	5.34d
	Mean	5.70bc	5.45d	5.73b	5.75a	5.68c	*LSD:* RSL = 0.026 MR = 0.023
WUE_{ET} (kg ha^{-1} mm^{-1})	1 m	10.7	10.3	11.1	10.0	10.3	10.5b
	1.5 m	13.0	12.3	12.1	15.4	14.0	13.3a
	2 m	12.4	12.9	13.9	13.3	11.8	12.9a
	3 m	12.0	10.7	10.7	12.4	9.1	11.0b
	Mean	12.0ab	11.5b	12.0ab	12.8a	11.3b	*LSD:* RSL = 1.156 ML = 1.034

**PUEfg calculations were taken by combining the growing season precipitation with the mulch effect and the fallow period without the mulch effect on the RSL treatments*
***Means followed by the same letter are not significantly different ($P < 0.05$)*

Statistical analysis revealed that both the surface treatments (RSL and ML) had significant effect on the efficiency of water use as a function of evapotranspiration. One wide (RSL-2) and one narrow (RSL-1.5) treatment showed a significant higher WUE_{ET} value than the other two treatments RSL-3 and RSL-1, which were similar. The effect of the mulch cover on the runoff was shown to have a significant higher WUE_{ET} value at 64% mulch cover with lower values on fully covered mulches, but there were small differences for bare and lower mulch cover treatments. The variation in WUE_{ET} value for various RSL and mulch cover reflects the more efficient conversion of water into maize grain yield due to the fact that more water was conserved in the 1.5 m runoff with 64% mulch cover than the wide full mulched treatment. As, one narrow (1.5 m) runoff treatments showed higher rainfall storage efficiency (RSE) in the basin as well as in the runoff area one might have expected that water should have been available to convert to yield. In contrast, on narrow runoff (RSL-1) treatments due to less dense canopy shading effect on the basin system of IRWH, the efficiency of conversion of water to grain was expected to be lower than wide treatments. In other words, the bare narrow RSL-1 had suppressed less soil surface evaporation (Es) compared to dense canopies of wide treatments. Besides the wide (RSL-3) treatments had also less contribution of additional in-field runoff that cause to lower the conversion of water to yield compared to RSL-1.5 and RSL-2 with higher in-field runoff to the basins.

From Table 7.6 therefore, it can be seen that, the WUE_{ET} variations could apparently be due to dual effect of in-field runoff and Es suppression from mulch and canopy shading. Moreover, despite the better yield found in narrow RSL-1 treatments, the fluctuation of water use efficiency therefore must be a reflection of the effect of surface treatments. A higher RSE and lower WUE_E were found for RSL-1.5 and in contrast with lower RSE on basin and runoff area (13.5 and 5.9%) and higher WUE_{ET} (12.9) calculated for RSL-2 treatments. However, these variations in the efficiency should be examined further by applying the water productivity as a function of transpiration of the crop (WP_{Ev}).

7.3.3.3 Water productivity (WP_{Ev})

The overall results indicate that the WP_{Ev} varied between 12.1 – 31.3 kg ha^{-1} mm^{-1} for maize grain yield (Table 7.7). The statistical results show that there were significant differences due to the effect of surface treatments (RSL and ML) on WP_{Ev}, but the combined effect of the treatments was not significant (Table 7.7). A different efficiency trend from the WUE_{ET} was observed *viz.* RSL-2, RSL-1.5, RSL-3 and RSL-1 for runoff lengths. Bare (ML0%) and lower mulch cover (ML12%) have significantly higher WP_{Ev} values, while the lowest value of WP_{Ev} was found for wide fully mulched treatment. The mean WP_{Ev} value for different RSLs and across mulch cover treatments ranged between 17.3 - 26.3 kg ha^{-1} mm^{-1} for grain yield. The results of WP_{Ev}, in general were higher than those in a previous study on maize under IRWH with various types of mulch, where the range of value was 10.7 - 11.7 kg ha^{-1} mm^{-1} (Botha, 2006), and also higher than other WP_{Ev} results where Passioura (2006) found a range between 8 to 15 kg ha^{-1} mm^{-1}. However, Gregory (1989) suggested that an equivalent WP_{Ev} value for a maize crop value would be 9.4 kg ha^{-1} mm^{-1} for semi-arid ecotope. In comparing different treatments of ML and RSL for the value of WP_{Ev}, some inconsistent was found in the degree of yield efficiency in terms of transpiration (Ev). However, from the results, it is revealed that all bare and lower mulched (Ml12%) RSL treatments had significant higher values than full mulch cover (96%). On the other hand, both RSL-2 and RSL-1.5 showed higher WP_{Ev} compared to RSL-1 and RSL-3 treatments in the experiment. Further explanations for these efficiencies need to be investigated.

Table 7.7 Water productivity for maize grain yield, for different mulch levels (ML) and runoff length (RSL) treatments in 2008/09 growing season.

Indicator	Treatment (RSL)	Mulch level treatments (ML%)					
		0%	12%	39%	64%	96%	**Mean**
WP_{Ev} (kg ha^{-1} mm^{-1})	1 m	21.6	19.4	20.7	17.1	16.2	19.0b
	1.5 m	28 .7	25.7	22.0	31.3	23.8	26.3a
	2 m	27.4	31.0	30.6	23.6	17.1	25.9a
	3 m	26.0	21.7	17.5	20.5	12.1	19.6b
	Mean	25.9a	24.4ab	22.7ab	23.1b	17.3c	*LSD:* RSL = 2.65 ML = 2.97

The data set of WP_{Ev} (Table 7.7) was plotted against rainwater available to the crop roots during growing period i.e. precipitation plus the run-on ($P_g + R_{on} = P_e$) (Fig.7.7). Result showed that, there is a reasonable relationship between P_e and WP_{Ev} for different RSL treatment across various mulching rate with R^2 value of 0.74, 0.61 and 0.74 for RSL-1, 2 and 3 m, respectively. As Hillel (1972) has remarked, it appears that the greatest promise for increasing water productivity lies in allowing the crop to continue transpiring during water shortage by controlling the processes of water losses, such as enhancing runoff to the basin and reducing soil evaporation which are both possible in the IRWH technique. When considering the link between crop productivity and transpiration it is tempting to use rainfall as guide. However, seasonal rainfall and transpiration are not synonymous and it is essential to emphasise that seasonal transpiration or direct water use by the crop is associated with crop productivity. Therefore, the considerable higher WP_{Ev} values for some treatments manifests that the advantage of bare or lower mulch cover plots to enhance runoff amount and make it available for crop productivity. On the other hand, the RSL-2 with lower mulch cover (ML12% and ML39%) and RSL-1.5 treatment with relatively higher mulch cover (64%) obtained highest water productivity (>30.0 WP_{Ev}) for a maize crop on the Kenilworth Bainsvlei ecotope compared to higher mulched plots of RSL-3 (< 20.0 of WP_{Ev}). So perhaps, the water infiltrating on the 1.5 and 2 m runoff strips is available to the maize roots and so has promoted a higher yield compared to water stored on 3 m strips possibly not being available to the crop.

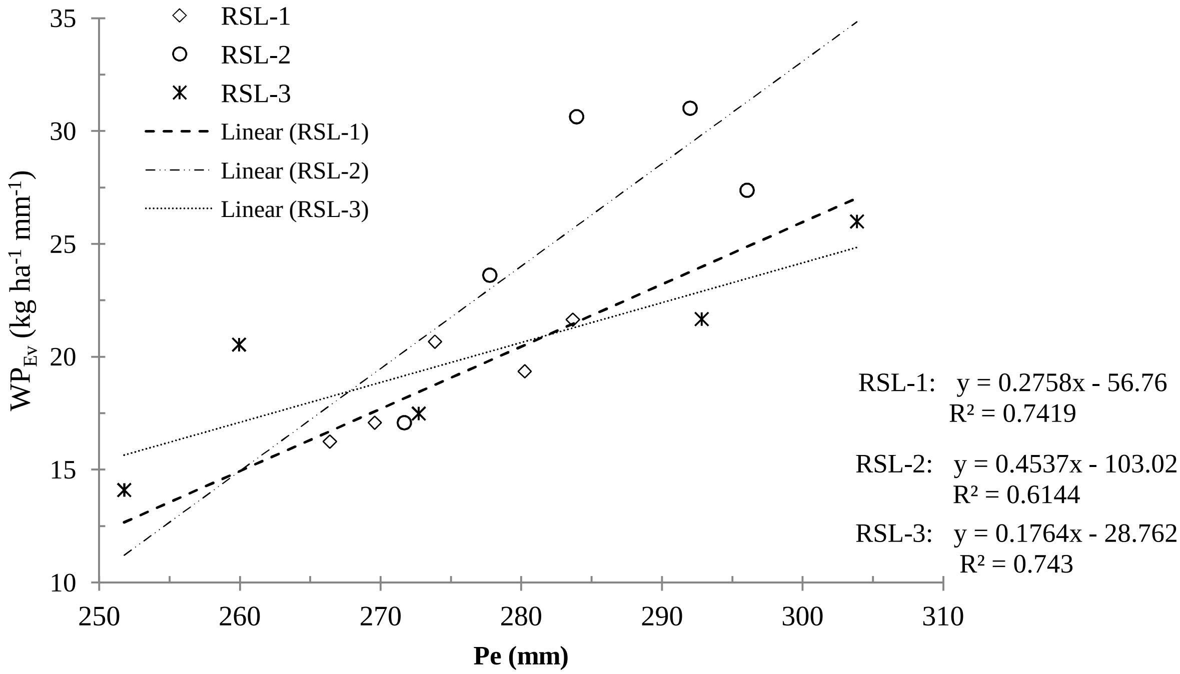


Figure 7.7 Relationship of seasonal rainwater (P_g+Ro=P_e) to crop water productivity (WP_{EV}) for cropping season 2008/09.

From the result obtained in this experiment, on deep fine sandy loam soil of Bainsvlei form, a 1.5 and 2 m runoff with bare or minimum mulch cover gives higher water productivity by accumulating runoff and by suppressing water losses due to evaporation. This result has important implications for the management practices of IRWH; as it confirms the need to optimize water use in terms of yield per unit water for transpiration in order to achieve higher WP in water scarce semi-arid conditions. In addition, it is important to describe the effectiveness with which rainwater was converted into grain yield and dry matter production. It was suggested that Passioura (2006); Botha (2007) and Malcolm Hensley (pers. comm., 2010, Dept. Soil, Crop and Climate Sciences, University of the Free State) that the advantage of using of rainwater productivity is that one considers long-term values of rainfall, which give a truer reflection of the ability of the management practices to convert rainwater to grain yield. One would have wanted more than 2 years data to be able to consider the rainwater productivity (RWP) over many more cropping seasons. Therefore, for the purpose of reliable recommendations concerning the best and alternative strategies of surface treatments and to compare the management options, it is desirable to have long-term yield predictions of the IRWH system. Thus, Malcolm Hensley (pers. comm., 2008, Dept. Soil, Crop and Climate Sciences, University of the Free State) suggested the use of simple empirical model with only long-term rainfall data as input o achieve this objective of evaluating management practices of the IRWH techniques in semi-arid area. Alternatively, long-term crop yields can be obtained with a crop growth simulation model such as DSSAT or APSIM or AquaCrop and compared to the transpiration, rainfall or water use.

7.4 Conclusion

The main focus of the study was to evaluate the potential role of the technique of IRWH in terms of water balance components and water productivity so as to assess the management practices under rainfed conditions. Therefore, the indicators used are: grain seed yield, above ground dry matter, HI, ET partitioned into Ev and Es, RSE, PUE_{fg}, WUE_{ET}, and WP_{Ev}.

Based on the results, the main conclusion is that the fraction of rainwater infiltrated in the basin area of RSL-2 increased with increasing mulch cover and thus it becomes more productive compared to other treatments. Secondly, the results also considered the critical periods for available plant water during the sensitive growth stages of the maize crop. The results showed higher plant available water for the narrow runoff while soil water content on the wide treatments dropped lower near to the LL value. Thirdly, seasonal ET values in the maize field of IRWH with different surface treatments varied in the range of 210 – 320 mm. The narrow RSL with lower mulch cover (ML12%) showed higher ET than the full mulch cover. From this study, it was found that Es losses were significantly restricted with increase mulch cover. The higher plant densities in wide RSL basins also efficiently reduce Es losses by the shading effect, whereas Ev was highest from full mulch cover plots and lowest from bare treatments.

The overall ET partitioned to Ev (Ev/ET) was higher for wide RSL (58%) and the full mulch also yields higher Ev/ET (66%) than narrow and bare or lower mulched plots. In general, these results showed that $Ev/ET \gg Es/ET$ for higher mulch cover treatments but for bare and lower mulched treatments the $Ev/ET \ll Es/ET$. This is probably due to the advantage surface treatments have in minimizing the unproductive water losses. The higher infiltration capacity of the soil reduces the Es losses. This is thus an indication that the suitability of the site for IRWH technique is unquestionable. From these results, the final grain yield did not show significant differences for various mulch levels, but the narrow runoff (RSL-1) showed higher yield than wide RSL-3 i.e. decreasing slightly with increasing size of the runoff. The performance of the HI is slightly variable among the treatments, which was indicative of the small variations in terms of direct yield evaluations for different treatments. The main reason for this small variation is due to the fact that more water for yield was harvested from bare plots than the mulch cover plots and presumably higher mulch conserves more water by suppressing the Es. So the two processes work to complement each other.

One of the parameters of the conservation tillage is the rainwater stored prior to planting. In this case, the RSL1.5 runoff obtained higher RSE compared to the rest RSL but it was not possible to compare the mulch effect on RSE as mulch was only applied for the second cropping season. In evaluating the use of precipitation from both the fallow (P_f) and growing period (P_g), the narrow runoff showed slightly better values than the wide treatments. In expressing grain yield per unit ET (WUE_{ET}) the 2 m and 1.5 m at ML64% mulch cover gave significant higher values than the two extremes of RSL treatments (RSL-1 and RSL-3). The WP_{Ev} values obtained from the experiment (2008/09) were highly variable in the range of 12.1 to 31.3 kg ha^{-1} mm^{-1} with higher values for RSL-2 and lower values for wide RSL-3 with full mulch cover. From the relationship of rainfall for productivity, WP_{Ev}, it became clear that there is a fairly reasonable correlation between the mulch rates and maize productivity per unit land.

CHAPTER 8

Characterize Profiles and Relationships of Temperature, Water Vapour and Wind Speed within Maize Canopy

"The interaction of environment with a plant is through the flow of heat energy.
There is no other way...
All energy absorbed by a canopy / leaf must be accounted for
(through storage within the canopy or loss from the canopy)
and hence the energy budget for a plant must balance."
David M. Gates (1968)

8.1 Introduction

IRWH is really a different approach to dry land farming, and as its focus is on water use, the different part of the Soil-Pant-Atmosphere water continuum (SPAC) are all an integral part of the system. Much research has been done on the soil and crop parameters within the IRWH technique. However, little effort has been invested in characterising the atmospheric components of this soil-plant-atmosphere system. Although many studies have measured the soil water balance as a source of water for the IRWH crop production technique, no-one has attempted to quantify the demand side of the equation from an atmospheric point of view. The wider adoption of IRWH has increased the research interest in IRWH and posed a number of questions about the least understood parts of the system, namely the micrometeorological processes and parameters. Therefore this study was initiated.

However, progress in understanding air profile relationships requires intensive and continuous micrometeorological measurements (Rosenberg *et al.,* 1983), with adequate attention given to high accuracy and reliability (Monteith and Unworth, 1990). According to Monteith and Unsworth (1990), with sufficiently precise instrumentation, profiles of wind speed, temperature and water vapour can be measured to represent some vertical gradients within a crop canopy. Therefore, central to many micrometeorological boundary-layer studies is the use of flux–profile relationships (Ni, 1997). The understanding of the profile relationships of climatic variables, together with flux estimation, is an essential step in matching the rainwater supply to the soil with the demand by the atmosphere and thus improved productivity and sustainability in any water conservation agricultural technique (Meyers and PawU, 1987). Therefore, to characterize profiles of temperature, water vapour and wind speed within a maize canopy, over this alternative arrangement of basin and runoff areas, is of paramount importance in evaluating the heat exchange and hence the available energy for evapotranspiration and thus water for crop production.

An assessment and evaluation of the vertical profiles of various climatic variables is of great importance as this would provide further knowledge of the thermal exchange processes between the crop canopy and surrounding environment. Several parts are necessary including the structure of the canopy, characterizing the vertical profiles and potential of thermal exchange processes with height, both within and/or above a crop canopy. However, exchange processes are still inadequately understood and thus the detailed mechanism of how heat and water vapour exchange processes occur within a maize canopy in a cropping system of in-field rainwater harvesting (IRWH) is unknown.

To verify and characterize the profile relationships is the first important step to having reliable flux estimation. This is in order to be able to evaluate the management practices from an energy balance as well as water balance point of view. A convenient and well-established approach to achieve this goal is to estimate the flux densities within the boundary layer that lies both within and above the vegetative area (Monteith and Unsworth, 1990). In a cropped field, the height where the heat energy exchange occurs depends on the profiles of dynamic meteorological parameters and on the flow within the thermal internal boundary layer (Arya, 2001). These processes are used not only to aid the understanding of turbulent transport but also as a tool that allows the vertical turbulent fluxes to be predicted from the more-easily measured and predicted vertical gradients of the profiles. In this regard, measurements of micrometeorological parameters (such as water vapour pressure, temperatures and wind speed) at different levels and during different crop growth stages will contribute to the understanding of how the net radiation in a crop land is balanced by the combination of sensible and latent heat fluxes and the conduction of heat flux through soil surface.

In this experiment therefore, vertical profiles at different maize growth stages are assessed, while making certain assumptions of horizontal heterogeneity of air temperature and water vapour and the wind speed drivers across the experimental field. Generally, from the measurements one can derive simple profile relationships that are then used to evaluate the heat and water vapour parameters that describe the transpiration and evaporation processes for wide and narrow strips under IRWH system. The key aims of this part of the study, therefore, were:

- to examine and characterize the vertical profiles of temperature, vapour pressure and wind, by comparing wide and narrow runoff strips during different growth stages; and
- to describe relationships between the wind speed (u) versus water vapour pressure (ea) and virtual potential temperature (θv) versus water vapour profiles within a maize canopy under wide and narrow runoff strips.

8.2 Theoretical basis and description of methods

8.2.1 Basic thermodynamic relationships

In thermodynamics, the density of air and total atmospheric pressure depend mainly on the effects of altitude, air temperature and water vapour pressure. Savage *et al.* (1997) mentioned that below an altitude of 750 m the correction of atmospheric pressure (P) may be insignificant, but above this altitude it is necessary in order to avoid systematic errors. The density of air refers to the total density of dry air ($\rho_d = M_a(P - ea)/RT$) and the density of water vapour ($\rho_w = M_w ea/RT$), where M_a and M_w are molecular mass of air and water, ea is the actual water vapour pressure (Pa), P is the atmospheric pressure (Pa), R = 8.315411 $Jmol^{-1}K^{-1}$ the Universal gas constant and T the air temperature (K). Assuming that the atmospheric pressure (P) at an altitude h is that at sea-level less the pressure due to the overlying air of depth h, as follows:

$$P = P_o - \rho g h \quad \textbf{8.1}$$

where ρ is the air density (Kg m^{-3}) and g is the acceleration due to gravity in m s^{-2}. P and P_o are atmospheric pressure at a given altitude (h) and at sea-level (0) in KPa, respectively.

The relationship between the change in temperature and pressure in a parcel moving adiabatically is used to relate the potential temperature (θ) to the atmospheric pressure. The potential temperature is defined as the temperature which an air parcel would have if it were to be brought down to a pressure of $\approx 10^2$ KPa adiabatically from its initial state as:

$$\theta = T(1000/P)^k \quad \textbf{8.2}$$

where P is air pressure in KPa and the potential temperature θ has the convenient property of being conserved during the vertical movement of an air parcel, provided that heat is not added or removed, and the exponent $k = R/c_p \cong 0.286$ where c_p is specific heat of dry air at a specific atmospheric pressure.

For moist unsaturated air, with Dalton's law of partial pressure ($P = P_d + ea$), where P_d is change in air pressure, one can apply a temperature dependant function to the specific gas constant for dry air, instead of humidity-dependant variables. Then, in practice, the correction is adapted to the temperature by using the virtual potential temperature (θv) as a parameter for heat exchange processes. According to Stull (1988), the virtual temperatures are defined as the temperature which dry air would have if its pressure and density were equal to that of moist air. To account for the effect of moisture on buoyancy force a virtual potential temperature (K) is defined as:

$$\theta_v = \theta(1 + 0.61q) \quad \textbf{8.3}$$

where the specific humidity is denoted by q and θv is the virtual potential temperature and is always greater than actual temperature and the difference between the two may reach as large as 7 K in warm tropical areas and be as small as 2 K in mid-latitude areas (Rosenberg *et al.*, 1983). Therefore, when buoyancy forces are involved, gradients of θv are preferable, rather than considering the actual potential temperatures (Plate, 1971; Busch, 1973; Rosenberg *et al.*, 1983; Arya, 2001).

Different studies express the water vapour in the air using different terms (Panofsky and Dutton, 1984; Rosenberg *et al.*, 1983). The parameter most often used in micrometeorology studies is the specific humidity (q) and is defined as the mixing ratio of the mass of water vapour to the mass of moist air containing the water vapour. In a broad sense, this is directly related to the actual water vapour pressure (ea), which is a fraction of the partial pressure exerted by the water vapour in the boundary layer. The actual water vapour pressure is usually lower than saturation vapour pressure (es), and both are dependent on temperature. According to Savage *et al.* (1997), Malek (1993) and Arya (2001) the preferred variable to compare and use in calculations of variation in water vapour is water vapour pressure variables instead of relative humidity which is temperature dependent.

8.2.2 Correction of psychometric temperature dependant constant

During data processing for profiles, the primarily focus should be on accurate expressions of the calculations of the so-called "temperature dependant constant" used in energy and mass transfer processes. This constant, affects the value of calculated heat energy flux densities and hence a full understanding of the variation of the psychometric constant, γ (KPa K^{-1}) is important. It is also expected that the removal of water vapour or evaporation from a surface is dependent on the atmospheric pressure. Therefore, the correction of the psychometric constant for a given atmospheric pressure other than sea level pressure is imperative. The common relationship is given as:

$$\gamma = \gamma_o(P/P_o) \qquad \textbf{8.4}$$

where γ is the psychometric constant at atmospheric pressure, P and γ_o is psychometric constant at sea level pressure, (P_o = 101.325 KPa), with values from 0.0655 to 0.0668 KPa K^{-1} as air temperature increases from 0 - 20^{o}C. The atmospheric pressure, P, is calculated at a given altitude (h) using Eq. 8.1 (Savage *et al.,* 1997).

Furthermore, using the theory developed by many researchers, and by following the factors and processes of the thermodynamic laws, it should be possible to calculate and to provide a relationship between water vapour pressure and virtual potential temperature in profiles within maize canopy. This leads to the appropriate interpretation of heat and mass transfer processes within a crop canopy.

8.3 Materials and methods

8.3.1 Experimental design and layout

The detailed climate, soil and topography characteristics of the Kenilworth Bainsvlei ecotope are given in Chapter 2 Section 2.3. The field layout and measurement position are shown in the diagram in Chapter 2 Section 2.4 (Fig. 2.2). The 1 ha maize field under IRWH was divided into four replicate blocks, with each main plot consisting of four IRWH runoff strip length (RSL) treatments (1, 1.5, 2 and 3 m) with rows extending the entire length of the field in the East-West (E-W) direction. For this study, the remaining block without any mulch treatments was used, by selecting only two RSL treatments, *viz.* 3 m and 1.5 m to represent a wide and a narrow runoff strip length, respectively. During the maize growing season, as part of continuous measurements, profiles of temperature, humidity, and wind speed measurements were performed within the maize crop canopy. During the measurement period, three consecutive growth stages with specific runs of measurement periods were selected. The growth stages represent early and late vegetative growth stages after the crop canopy has attained a height of 1.2 m and 1.6 m, and at maximum canopy height (average of 2.2 m) when the crop is in the reproductive stage.

Micrometeorological profile measurements were made at four levels and the sensors were installed at various heights by shifting them on vertical poles, according to the crop growth. The heights were changed three times through the growing period, as indicted in Table 8.1. The focus of the analysis was on the vertical profiles of the potential virtual temperature, water vapour pressure and wind speed, during the three selected growth stages, from measurements taken at four heights within the maize canopy on both wide (3 m) and narrow (1.5 m) runoff strips. When the crop attained a height of 1.2 m and later 1.6 m, the set-up of the instruments were fixed at the four prescribed levels of 0.3, 0.6, 0.9 and 1.2 m and 0.4, 0.8, 1.2 and 1.6 m respectively, above the soil surface within the canopy. When crop height was at a maximum (2.2 m), at reproductive stage, the sensors were moved up to levels of 0.55, 1.10, 1.65 and 2.2 m (Table 8.1).

Table 8.1 General information about the days of the measurements and sensor position: z_i are heights above ground surface levels of the micrometeorology measurements; DOY represents day of year.

Growth stages	Early vegetative	Late vegetative	Maximum height
Observed period (Date)	5-11 Feb., 2009	20-25 Feb., 2009	10-15 Mar., 2009
DOY	36-42	51-56	69-74
Profile position	Height (m)		
z_1 (m)	0.30	0.40	0.55
z_2 (m)	0.60	0.80	1.10
z_3 (m)	0.90	1.20	1.65
z_4 (m)=*hc**	1.20	1.60	2.20

**Crop height at top level = hc*

In these canopy profile observations, the four layers of measurements were denoted as: "*upper portion*" (UP), "*mid-upper*" (MU), "*mid-lower*" (ML) and "*lower portion*" (LP). These portions or layers of the maize canopy represent the top canopy layer, upper part above the midpoint, lower part below the midpoint and the bottom layer respectively. The variation in measurement, in these strata (layers) of the vertical profiles, gives an opportunity to characterize the micrometeorological parameters and their interactions within crop canopies.

8.3.2 Measurements

In order to measure the profiles within a maize canopy, a tripod stand-pole with extended arms was erected in both wide (RSL-3) and narrow (RSL-1.5) runoff section areas. An identically instrumented tripod was placed in the centre of a runoff section of each treatment by selecting the third runoff strip on the southern side from the four consecutive runoff strips making up each treatment plot (Fig. 8.1). To ensure that the measurements made by different sensors at same height in narrow and wide runoff strips, the tripod poles and arms were checked frequently. Intensive care was also taken not to allow the sensors to touch plant parts, in particular in narrow runoff strips. The position of the sensors was upwind of the vertical pole holding them (prevailing N-NW wind direction). Plant samples were taken at 10 day intervals from 15 Jan. to 25 Mar., 2009 to monitor the basin leaf area ratio (BLAR), and plant height, the dates being 25, 35, 45, 55 and 65 days after planting (DAP). The measurement procedures for leaf area and plant height are described in Chapter 2, Section 2.3.

Figure 8.1 Sensor arrangements in the runoff section within the maize canopy at 1.6 m crop height on 25 Feb., 2009 for the 3 m length runoff strip.

8.3.3 Instrumentation

The following measurements were performed at four levels within the maize canopy:

(a) wind speed was measured using three-cup wheel Sentry anemometers (Model 03001) with stalling speed of about $0.15ms^{-1}$; and

(b) temperature and humidity were monitored using HMP50 temperature and relative humidity probe, which contains PRT and Vaisala-INTERCAP sensors for temperature and relative humidity, respectively (Model HMP50 Campbell Scientific, USA). These HMO50 sensors were housed inside white plate radiation shields (Campbell 41303-5A Model) (Fig. 8.1).

The sensor positions within the crop canopy at the four levels are illustrated in Fig 8.1 for the 1.6 m crop height. All micrometeorological data were recorded on a CR1000X datalogger (Campbell Scientific, USA) every 5 min. and averaged over one hour. Instrumentation was frequently checked and data regularly downloaded to a laptop computer with some overlap from the previous download.

8.3.4 Data handling and processing

In order to compute the necessary meteorological parameters, several steps of data processing are required. These steps include: data downloading directly from the datalogger in the field and data storage in simple spreadsheet templates. Secondly, raw data was checked and a decision was made about data quality and availability for continuous time periods, before implementing intensive data processing. As parameters for expressing humidity and temperature are interconnected, they must be manipulated to calculate the required derived parameters. The measured relative humidity, RH (%) is defined as:

$$RH = 100 * (ea/es) \qquad \textbf{8.5}$$

where es is saturated vapour pressure (KPa), calculated using the following equation:

$$es = 0.6108\text{exp}\ (17.2694T/273.3 + T) \qquad \textbf{8.6}$$

where T is the temperature (^{o}C).

Once the, es is calculated, it is a simple matter to use measured RH and ratios to calculate the actual vapour pressure, ea values (Allan *et al.,* 1998). Hence the moisture profiles can be expressed in the form of actual water vapour pressure in KPa unit rather than the relative humidity in %.

In the case of profile temperature measurements, it is essential to consider the theoretical bases of the temperature dependant constants. The psychrometeric constant (γ) determines the correct values of heat and mass densities in the boundary layer. This constant is also dependent on T, ea and on acceleration of gravity (g) and atmospheric pressure (P). In the profile analysis, θv and ea were calculated using the above procedure, as follows. The γ for this altitude (h = 1354m) was calculated as 0.055 KPa K^{-1}, assuming that the density of the air, ρ is 1.211 kg m^{-3}, and the atmospheric pressure, P = 85.245 KPa was calculated using Eq. 8.1. Virtual potential temperatures used in the analysis of the profiles were calculated according to equations 8.3 and 8.4, in order to remove the temperature variations caused by changes in pressure and altitude of an air parcel.

8.3.5 Method of statistical analysis

To compare the differences in the observations between the two groups, wide and narrow runoff strips, for each layer in the profile, a statistical data analysis was conducted using a two-tail paired t-test procedure with SAS 9.1.3 statistical software for Windows (SAS Inst. Inc., 2006). Significance levels of $P \leq 0.05$ and $P \leq 0.0001$ were used based on the variability associated with the measurements. These comparisons were carried out for three different periods during the season. In addition to statistical methods, graphical and tabular representations were used to illustrate and compare the diurnal variations of the profiles within the canopy for specific days and hours. The relationships were expressed using empirical regression procedures.

8.4 Results and discussion

8.4.1 Maize canopy structure

During the selected vegetative and reproductive periods, the maize crop was growing rapidly (Fig. 8.2). The wide (RSL-3) and narrow (RSL-1.5) treatments follow the same trend for both crop height (hc) and basin leaf area ratio (BLAR), but the wide runoff treatment shows a higher BLAR.

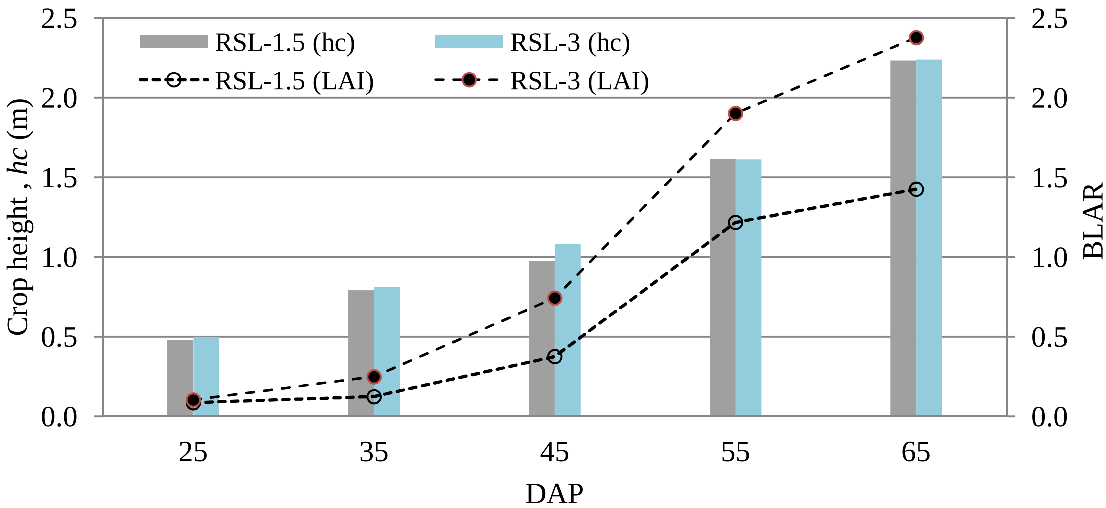


Figure 8.2 The course of crop height (*hc*) and basin leaf area ratio (BLAR) during vegetative and reproductive stages at 10 day intervals from middle of January to March, 2009.

The BLAR trend showed that in both RSL treatments, the BLAR increased with the plant growth during 35-55 DAP and reached a "plateau" after 65 DAP (Fig. 8.2). At later growth stages, a significant difference was found for BLAR between wide and narrow runoffs treatments. However, the statistical analysis of the plant height data revealed no significant differences between treatments. The wide runoff area dictated that the basin area must have more plants (6.4 plants m^{-2}) (as both treatments had same plant population per total land area), therefore effectively giving a higher BLAR over that part, than the narrow runoff plots which had fewer plants in each basin area (3.3 plants m^{-2}) as there were more basin areas per total land area. These vegetation characteristics, plant density and BLAR, have an effect on the processes of heat and water vapour within the maize canopy at different growth stages. The variation in canopy structure of a maize crop under IRWH will be an important consideration when evaluating the vertical distribution of meteorological variables such as temperature, water vapour and wind and their role in the energy balance of the canopy and soil surface.

8.4.2 Comparison of profiles within the canopy

Table 8.2 shows the summary of the statistical results for each of the parameters wind speed (u), θv and ea within the canopy at a crop height of 1.2, 1.6 and 2.2 m, which correspond to a) early vegetative, b) late vegetative and c) maximum crop height stages.

Table 8.2 Statistical comparison between wide and narrow RSL treatments; for hourly wind speed (u), virtual potential temperature (θv) and actual water vapour pressure (ea) within the canopy at 4 levels for a) early vegetative stage when crop height = 1.2 m (n=144), b) late vegetative stage when crop height= 1.6 m (n=96) and c) at maximum crop height of 2.2 m (n=120).

Parameters	Layer	**a) Early veg. stage**		**b) Late veg. Stage**		**c) Max. crop height**	
		Height (m)	Sig. level	Height (m)	Sig. Level	Height (m)	Sig. Level
Wind speed (u)	LP	0.30	*	0.40	**	0.55	**
	ML	0.60	ns	0.80	**	1.10	**
	MU	0.90	**	1.20	**	1.65	**
	UP	1.20	ns	1.60	**	2.20	**
Virtual pot. Temperature (θv)	LP	0.30	**	0.40	*	0.55	ns
	ML	0.60	**	0.80	*	1.10	ns
	MU	0.90	ns	1.20	*	1.65	*
	UP	1.20	**	1.60	**	2.20	*
Water vapour Pressure (ea)	LP	0.30	**	0.40	**	0.55	**
	ML	0.60	ns	0.80	**	1.10	**
	MU	0.90	ns	1.20	**	1.65	**
	UP	1.20	**	1.60	**	2.20	**

and significance levels at P value P< 0.05 and P<0.0001, ns= not significant differences.*

During the early vegetative growth stage, the profiles of all three parameters showed statistical variations in some of the different layers but not at all levels (Table 8.2a). The wind speed profile at MU had highly significant differences at (P < 0.0001) between wide and narrow plots but in the top (UP) and middle (ML) part of the canopy there were no significant differences between the wide and narrow runoff strips. But both θv and ea had highly significant differences in the upper (UP) and lower parts (LP) of the canopy.

In contrast to the crops at the early vegetative stage (hc = 1.2 m), when the crops attain a 1.6 m height (during late vegetative stage) there were significant differences in all the measured variables (u, θv and ea) between wide and narrow runoff treatments. In particular, u and ea showed highly significant differences at a P value < 0.0001 significant level (Table 8.2b) at all sampling levels. When maximum plant height (average of 2.2 m) was reached after 65 DAP, statistical results showed highly significant differences for the profiles of u and ea between the wide and narrow runoff strips (Table 8.2c). This is in agreement with results obtained for all the profile-levels during late vegetative stage. However, the θv below the middle of the canopy height was not significantly different, even at P value of 0.05, between wide and narrow runoff, while the upper two levels were significant at $P < 0.05$. The reason for the less or non-significant differences of θv in lower portion is not clear. Nevertheless, with little turbulence under low wind conditions (< 1 m s^{-1}), almost all the heat exchange between the leaves and air above, occurred in the top half of the canopy. The bottom half of the canopy is a very weak heat sink in both wide and narrow runoff strips due to presence of fewer leaves.

8.4.2.1 Early vegetative growth stage profiles

Representative profiles of u for the morning and daytime for a series of periods of 08:00 - 13:00 hrs typically have low values near the surface and increase with height through the canopy (Fig. 8.3). In general, the wind speed was higher in the morning and becomes calm during midday (Fig. 8.3). The wind speed increases from the lowest level near the ground (LP) to the upper layer (UP) of the crop for both treatments at all times which is considered a typical pattern within a crop canopy (Monteith and Unsworth, 1990). During the morning (Fig. 8.3a), the wind speed in narrow runoff is much higher than in wide runoff at all heights and times. However, as the wind speed decreases on both RSL, by midday (11:00 - 13:00) the differences between them become insignificant at 13:00 (Fig. 8.3b).

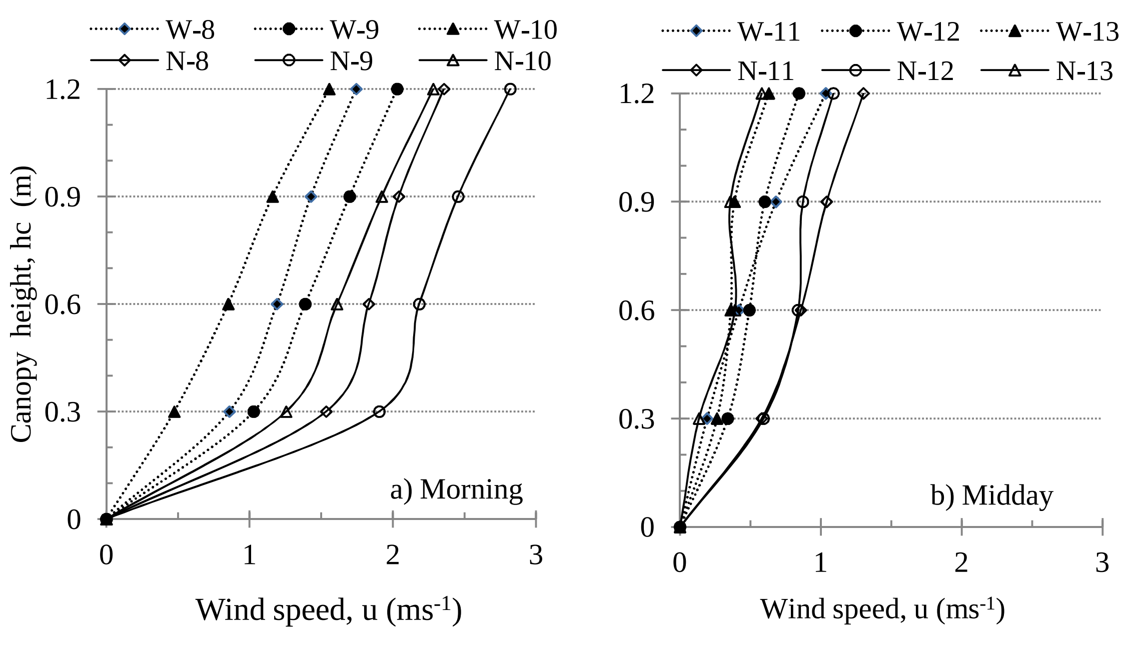


Figure 8.3 Observed wind speed, u (ms^{-1}), profile measurement during (a) morning and (b) midday within a maize canopy with crop height, hc of 1.2 m in wide and narrow RSL, at Kenilworth Bainsvlei, on 06 Feb., 2009 (47 DAP). N-i and W-i represent narrow and wide strips at specific i hour of measurement.

The hourly profiles of water vapour in the morning (Fig. 8.4a) and around midday (Fig. 8.4b) both show sigmoid-shaped ea profiles, within the canopy with the values at LP and UP being similar. In the wide RSL, for ML and MU parts of the canopy, the profile of ea decreases slightly (lapse) with height and returns back to a higher value in the UP of the canopy (Fig. 8.4) because of the higher wind speed in this part of the canopy (UP) (Fig. 8.3). In narrow RSL, the decrease is from ML to UP, near the top of canopy with peak ea in the ML part of canopy. At this stage of vegetative growth, in both wide and narrow runoff sections the moisture concentration in the UP layer decreases as the day progresses with increasing air temperature and the resulting increases in evaporative demand. In the MU portion of the canopy the ea values decrease with height in both wide and narrow runoff strips (Fig. 8.4a).

In the middle layer of the canopy the ea values show a slight decrease in ea with height in both wide and narrow runoff strips (Fig. 8.4a). The change of ea with crop height and the effect of turbulence due to higher wind speed with height caused the shape of the profiles on wide and narrow runoff strips. This is probably due to the fact that wind does not penetrate into narrow runoff. However, the values of ea decrease throughout the day at each different profile height in both the wide and narrow runoffs. For example at this vegetative stage, in the daytime, the highest ea values (1.51 – 1.62 KPa) were observed during the morning hours and the lower ea were measured during the late afternoon hours at 16:00 (1.10 – 1.21 KPa) before sunset. This would provide a larger vapour pressure deficit at this time which is then part of the driving force for the highest evapotranspiration rate to occur at this time of day, probably as one would expect.

The θv profiles within the canopy, at crop height of 1.2 m, were the same shape as the water vapour profiles measured in the daytime on that particular day (Fig. 8.6f). Figure 8.6e shows a slightly higher θv in LP the lowest part of the wide canopy, but within the layers of MU and UP the temperature differences were small. During the morning hours no differences were observed between wide and narrow at ML and MU layers of the canopy. For example, there is a higher θv during the morning time in the ML part of the canopy, with small changes LP-UP of 1.2 K and 0.6 K for both the wide and narrow RSL respectively, and maximum θv were observed at all heights in the late afternoon hours (Fig. 8.4g).

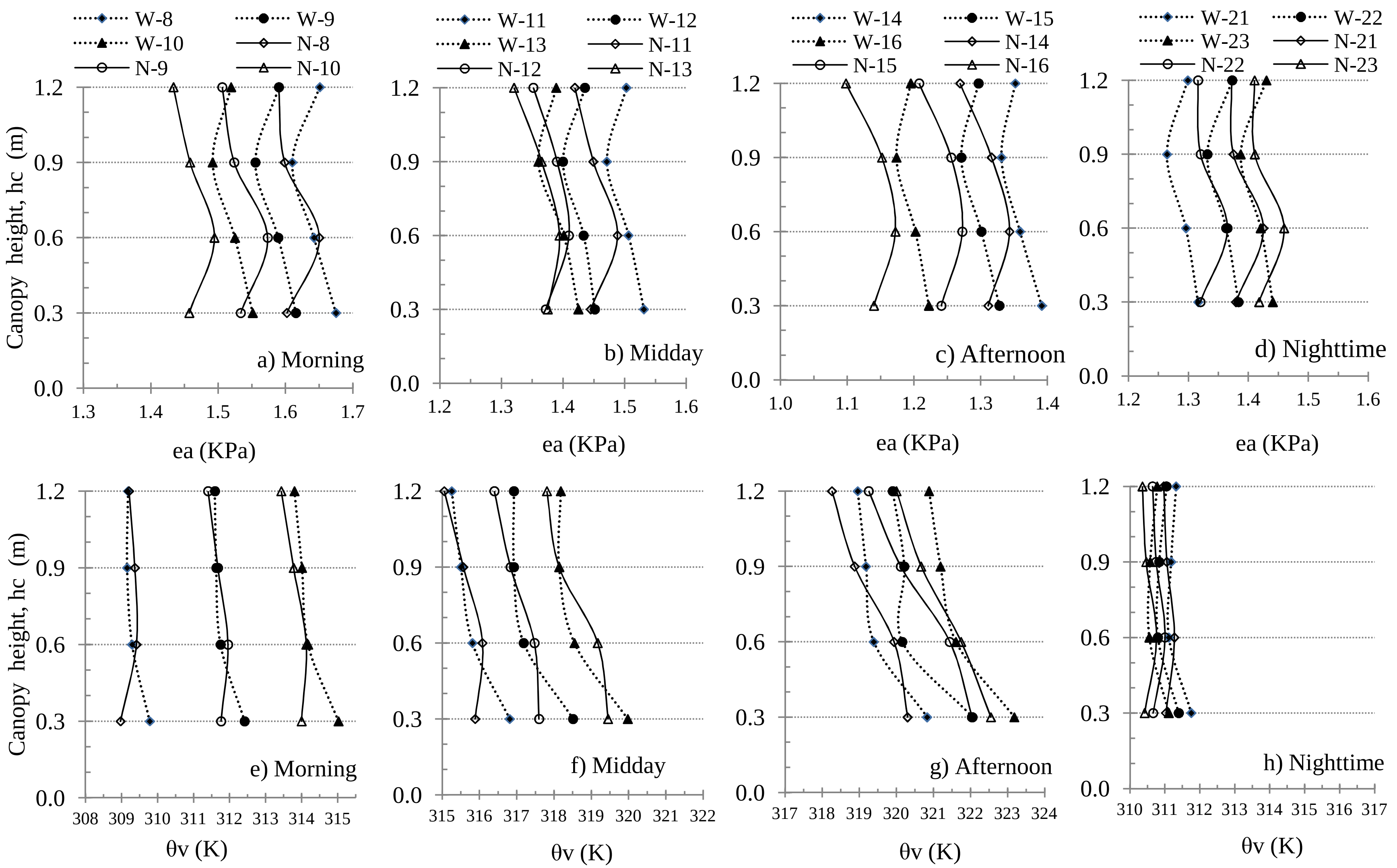


Figure 8.4 Hourly water vapour pressure and virtual potential temperatues profiles in the narrow and wide for the morning (8:00-10:00), midday (11:00 & 13:00) , afternoon (14:00-16:00) and nighttime (21:00 & 23:00) at Kenilworth Bainsvlei, on 6 Feb., 2009 (47 DAP). N-i and W-i representing (i) time of day (h) of measurement on narrow and wide strips respectively

During the daytime, in the wide row runoff areas, the lowest (LP) and the second lowest (ML) values for θv are always higher than the rest of the canopy, such that θv wide is greater than θv narrow (Fig. 8.4e&f) and attained a maximum value > 323K for wide and narrow rows at 16:00. This implies that there is a build up of heat in the lowest layer nearest to the soil surface in the wide treatment. During the midday period, it seems that the temperature in the narrow rows remains the same at both ML and LP while the wide rows have a higher temperature especially at LP (Fig.8.4f&g). The wide strips have a lower θv value at ML during the midday period than the narrow θv creating a steeper gradient in this layer, but at MU they were most similar. At the lowest level LP the narrow rows continue to have a lower θv than the wide rows, probably due to the shading on this runoff section from closer plant rows.

At the afternoon (Fig. 8.4b&c), ea profiles remain unchanged from midday profile measurements, but the values of ea are lower, with lowest ea having occurred at 16:00, after a steady decline through the afternoon and then a sudden increase in ea again around sunset. The value of ea in late afternoon (16:00) in UP and ML of the canopy was lower by 0.25 KPa compared to the midday profile measurements following a typical diurnal ea cycle (Fig. 8.4). Fig. 8.4h shows θv measurements during the nighttime with slightly sigmoid-shaped profiles, and increasing at the LP part of the canopy in wide runoff and to a slightly inversion condition through the rest of the canopy. Conversely, in the narrow runoff the θv profiles illustrate inversion in the lower part half of the canopy and then lapse conditions, from the LP and towards to the top of the canopy. The lower middle part of the canopy in the narrow runoff strips is warmer than the wide runoff at night. Therefore at night (Fig. 8.4h) under low wind speed conditions a free convection state occurs and turbulence is generated by the relatively warmer canopy in the narrow runoffs. This is the reason why the ML part of the canopy shows inversion in wide rows for both ea and θv profiles (Fig 8.4d and Fig. 8.4h). It is expected that the net radiative energy loss at the MU and UP can be balanced by the available heat source within the canopy.

The diurnal changes in wind speed showed higher values in the narrow than wide runoff, and reached peak at 09:00am with values 2 & 2.8 ms^{-1} and 1.4 & 2.2 ms^{-1} on the UP & LP parts of the canopy, respectively (Fig. 8.5a & b). However, θv on the lower portion of the canopy was shown to increase from the morning and reached peak in late afternoon with more variation in the narrow than wide strip (Fig. 8.5c & d). From the above discussion it can be seen that the aerodynamic characteristics of the canopy (vegetation) structure played a big role within the canopy and up into the boundary layer above the canopy (see also Chapter 9 Section 9.3.4). Experimental studies on agricultural crops (Shaw and Schumann 1992; Wilson *et al.*, 1982; Ni, 1997) have shown that turbulence within and just above plant canopies was dominated by highly coherent eddies with length scale and canopy structures (not measured). The variation in turbulence, accounts for most of the vertical transport of momentum, heat and water vapour within the canopy in both wide and narrow strips. In the system of IRWH with wide row spacing, the influence of canopy structure would therefore be imposed through changing boundary conditions and its influence on turbulent air flow around the crop environment in the runoff area.

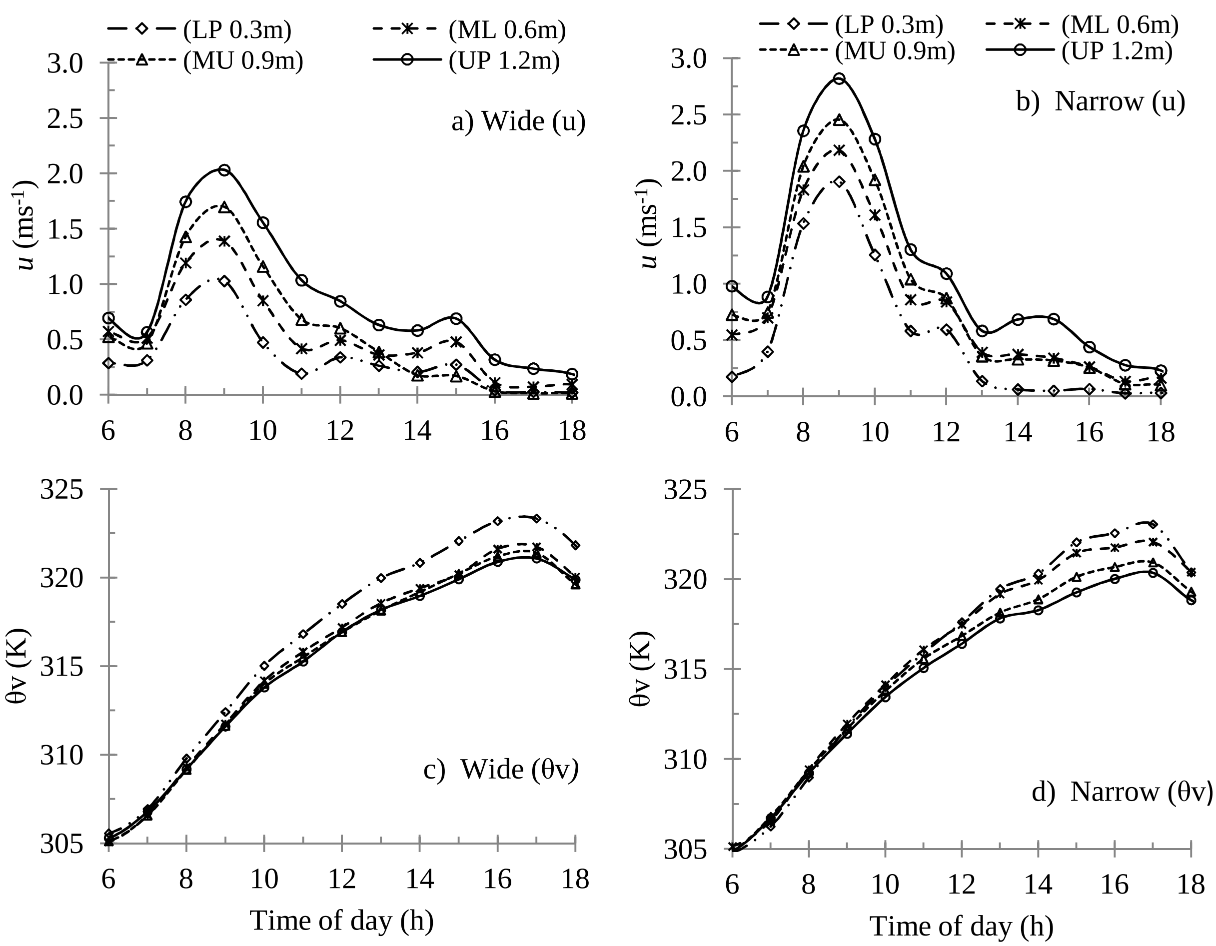


Figure 8.5 Diurnal changes of wind speed (u) and potential temperatures (θv) through the daytime on 6 Feb., 2009 on wide and narrow runoff strips.

8.4.2.2 Late vegetative growth stage profiles

Profiles in Fig. 8.6a&b illustrate that in the wide runoff, the wind increases from 8:00 - 10:00am and is greater than the narrow runoff at all times. In contrast, during night time the wind was blowing at about the same magnitude within the canopy of both runoff strips sizes, and it is constant in the middle part of the canopy and increased slightly at the upper level of the canopy in the narrow strips (Fig. 8.6a&b).

An illustration of typical daytime and nighttime ea and θv within canopy profiles is shown in Fig. 8.6c&d for the canopy height 1.6 m. At midday, in narrow, inversion and lapse conditions show only a little change except a drop in temperature of 2 K between 9:00 and 11:00 (Appendix 8.2b). For the wide rows, the highest ea values were nearest the soil surface, the lowest in canopy with a slight increase in ea again in the top (UP) later. For the narrow runoff the peak ea is at ML in the lower middle of the canopy and then decreases to the lowest level (LP) and further up the canopy to the top of the canopy (UP). These differences are about half to 0.1 KPa in size across the height of the canopy and up to 0.2 KPa differences between different times of the day. For the narrow runoff area, the ea profiles demonstrate a decrease from base of canopy upwards (from LP to ML to MU) showing inversion of ea profiles. As the highest ea is in the lower part of the canopy, it may imply that the water that evaporated from the lower leaves is not leaving the canopy due to dense vegetation. In the diurnal trends, higher *u* was observed in the wide than narrow strips, during a typical calm day with wind speed of less than 1 m s^{-1} (Fig. 8.7a). This is opposite to the windy period shown on 6 Feb. (Fig. 8.5), hence under these calm conditions, above the wide runoff strip, most of the heat exchange is by the buoyancy force within the lower part canopy. For example, in wide runoff the diurnal change in *ea* showed continuously higher values at the lower portion of the canopy (LP & ML) around midday (11:00-13:00) (Fig. 8.7c & d). However in narrow strips, due to small eddies around the plant leaves and closer plant rows across the runoff, the *ea* on ML reached peak value at 11:00, then ea remains higher in the lower part of the canopy (Fig. 8.7d), probably due to low wind speeds of less than 0.2 m s^{-1}.

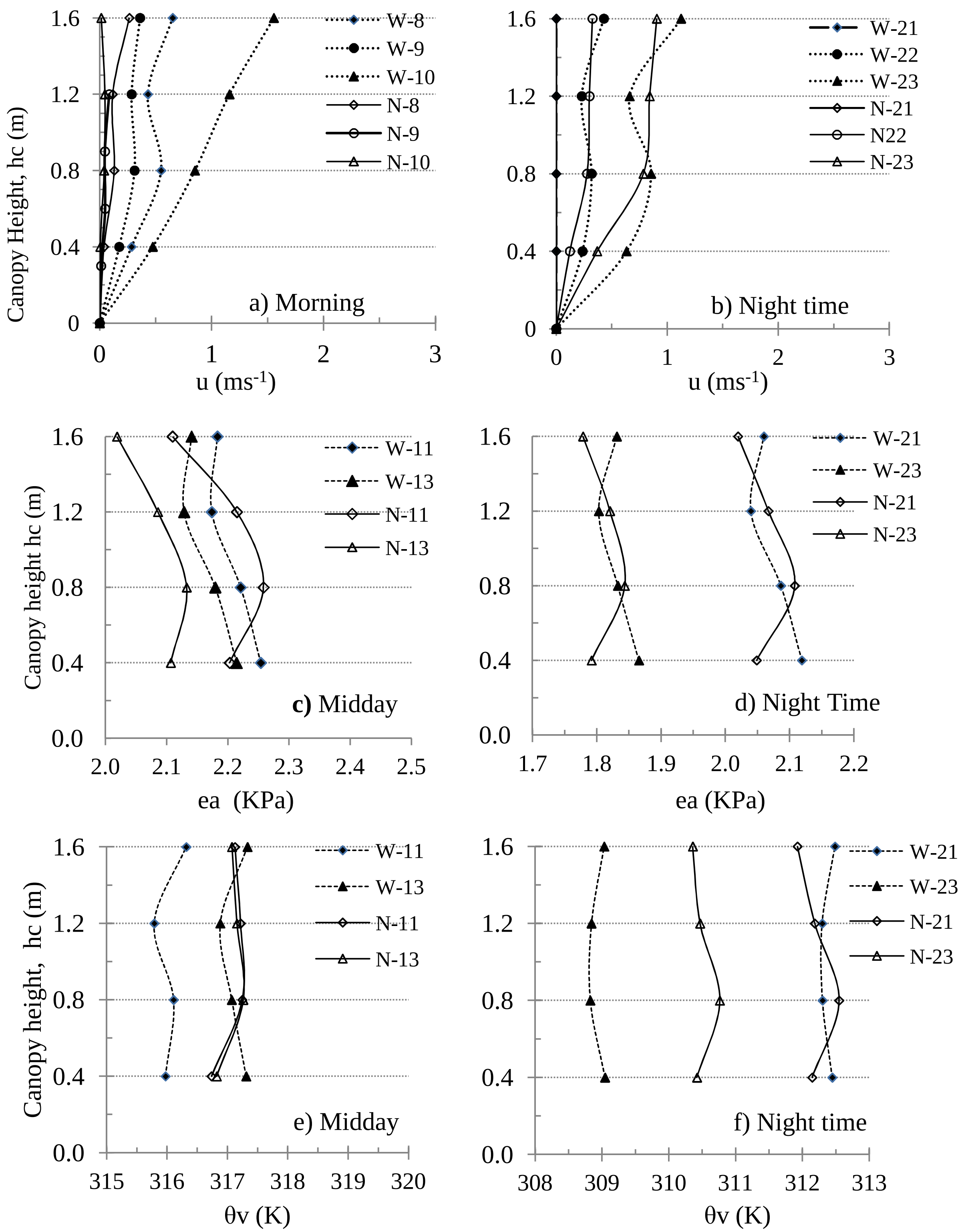


Figure 8.6 Hourly wind speed (u), water vapour pressure (ea) and virtual potential temperature (θv) profiles in both narrow and wide for either the morning (08:-10:00) or at midday (11:00 & 13:00) and nighttime (21:00 & 23:00) at Kenilworth Bainsvlei, on 21 Feb., 2009 (62 DAP). N-i and W-i represent narrow and wide strips at specific i hour of measurement.

Therefore, under calm wind conditions, in particular with narrow strips, temperature and water vapour have small profile gradients and low turbulent mixing in the lower part of the canopy, so play an important role in suppressing the evaporation (Fig. 8.6 and Fig. 8.7). In a study of temperature and water vapour pressure within maize canopy, Stigter *et al.* (1976) described the key role played by the soil surface in creating local microclimatic variations within lower part of the canopy, under less windy conditions for a maize crop with narrow rows.

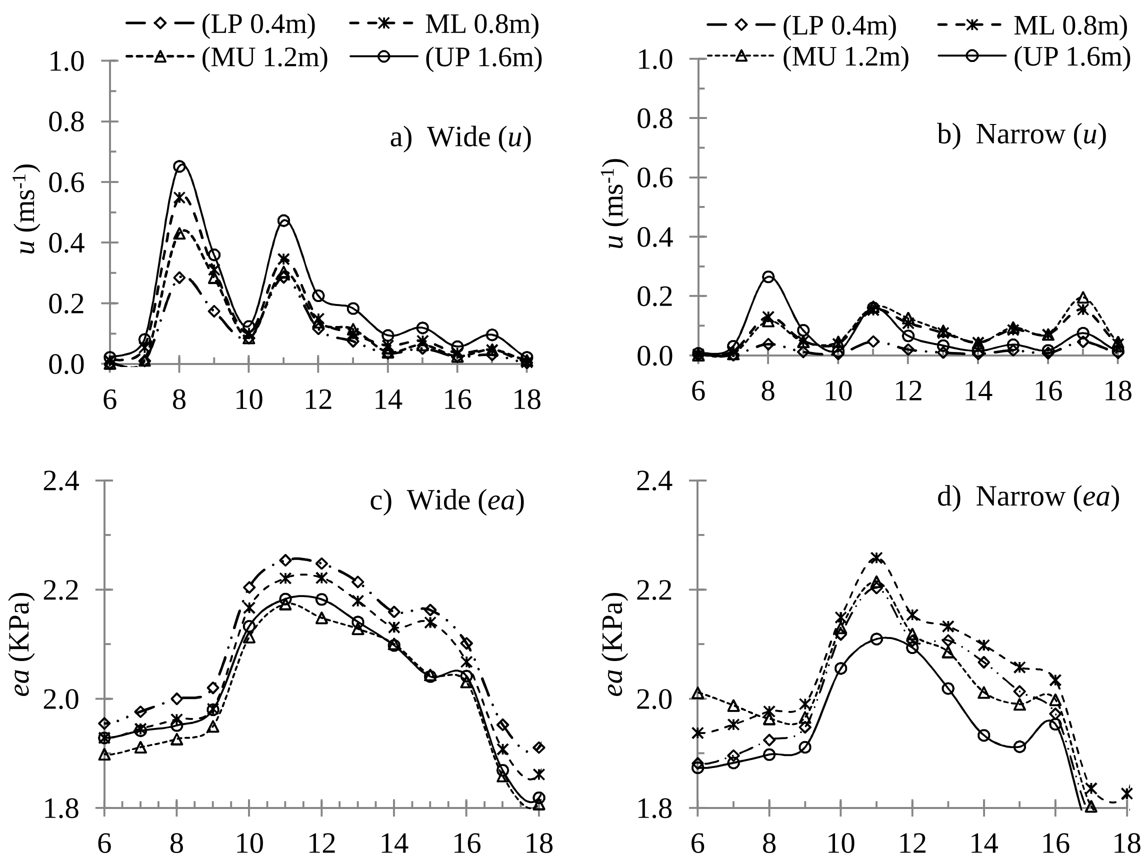


Figure 8.7 Hourly windspeed (u) and water vapour pressure (ea) at four heights for the narrow and wide throughout the day at Kenilworth Bainsvlei, 21 Feb., 2009 (62 DAP).

8.4.2.3 Maximum canopy height profiles

The wind profiles within canopy had a similar trend with the exception at 8:00 and 11:00am in the narrow strips but small variations occurred in the upper part of the canopy during nighttime (Fig 8.8a-c). The *ea* in a wide runoff at UP and LP throughout the day is always higher than those measured in narrow strips (Fig. 8.8d-f). At the middle part of the canopy (ML and MU) the ea had greater values in the narrow runoff during the morning and then in the afternoon and late evening hours, while the difference in ea between narrow and wide is less or equal.

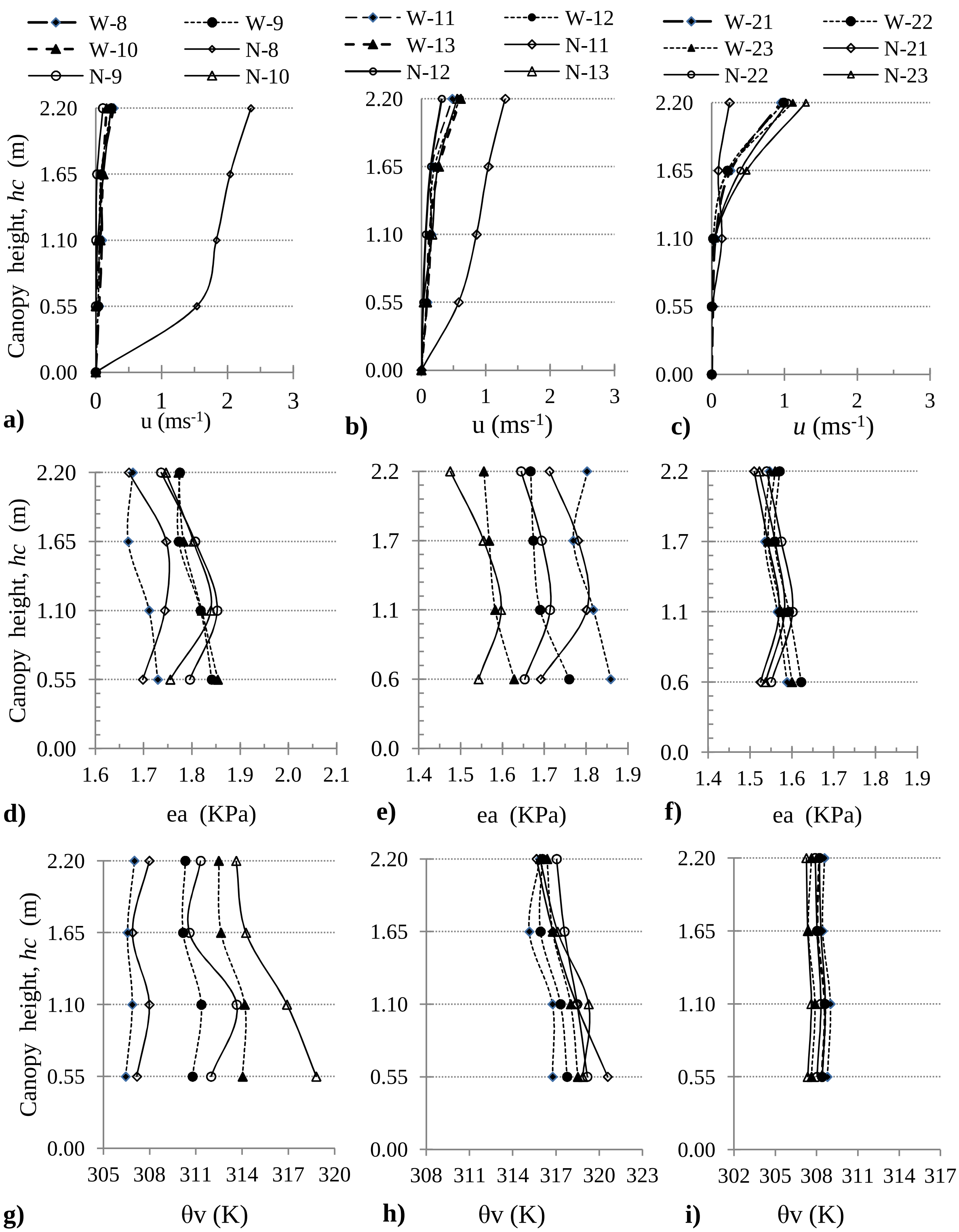


Figure 8.8 Hourly wind speed (u), water vapour pressure (ea) and virtual potential temperature (θv) profiles in the narrow and wide for either the morning (08:-10:00) or at midday (11:00 - 13:00) and nighttime (21:00 - 23:00) at Kenilworth Bainsvlei, on 11 Mar., 2009 (80 DAP). N-i and W-i represent narrow and wide strips at specific i hour of measurement.

The profiles show that the location of maximum temperatures varied within the vertical canopy profile for ML and LP for narrow and wide runoffs (Fig8.8g-i). From 10:00 until 16:00 the highest temperature during this stage were recorded in the LP (except 1 h) for both the wide and narrow treatments (App. 8.3). This would indicate that under the IRWH system the heat sink is lower than the upper part of the canopy, with a maximum difference in temperature between the UP and LP reaching 5 K at 10:00 and 11:00 on the narrow treatment. In contrast, the highest gradients on the wide treatment were at 16:00 and reached 6 K, which could have been caused by the slanted rays of the sun that late in the afternoon reaching through the wide runoff area directly onto the leaves (Fig. 8.9a&b). Perhaps, the differences between the warmer parts of the canopy can be attributed to the layout of the runoff strips or the latitude of the site and the date being in March, so these details would have to be considered when comparing with the literature reports. For example, these features correspond to the results of Raupach (1979) and Denmead and Bradley (1968). They described that a notable feature in all profiles within the maize canopy, is the existence of “hot spot” at about 2/3 canopy height during day and high radiation periods. Therefore, it is evident that, the canopy was a net heat source for most of the day with strong heat production around leaves on the top layer of the canopy. This meant that, the lower portion or bottom part of the canopy constituted a weak heat sink for most of the day time. Moreover, under full canopy stage, that particular day illustrates well how the entire or core canopy may heat the air surrounding it, and creating a temperature variation within canopy rather than changing in a vertical one.

The figures of 8.8g-i also clearly demonstrate that at morning and midday time the narrow runoffs are slightly warmer than the wide ones but in late afternoon it can be seen that the reverse conditions occurred with the wide rows being a higher θv. In summarizing the typical sequence of observed ea and θv profiles structures is similar to the profiles of the late vegetative growth stage, as discussed in section 8.4.2.1. However, there may be some profile magnitude differences as a result of diurnal variations of net radiation and other energy fluxes at the soil surface and within the canopy (Chapter 10, Section 10.4.3.3). Diurnal changes in temperature and water vapour were experienced over the wide and a narrow runoffs strip due to the air in the canopy being heated in the morning and cooled rapidly at sunset or night fall (Fig. 8.9c&d). Typical examples of the magnitude of measured values at selected times during the morning, midday, evening and nighttime hours over the wide and narrow treatments are shown in Appendix 8.3a for θv profiles and Appendix 8.3b for water vapour profiles.

As can be seen in Fig. 8.9a in a wide runoff area the daytime ea profiles show a slight decrease with height for much of the canopy and the surface layer above (LP); a slight increase (inversion) in the UP of the canopy is probably due to increased transpiration from the leaves in that layer. In the case of nocturnal (21:00 - 23:00), vapour pressure shows a similar trend to the daytime profiles but with very slightly changes (not shown). However the night time profiles may be more complicated due to the dew formation (Jacobs and Nieveen, 1995) and so will not be addressed here. A low evaporation rate probably continues from the soil surface as a result of a free convective state that dominates in the lower part of the canopy.

The vapour pressure peaked in the morning, from 10:00 until 11:00 in both the wide and narrow treatments; somehow this was then followed by the increase in temperature which showed a wide rising plateau from 11:00 until a peak at 16:00 in the wide and starting an hour earlier on the narrow treatment. This meant that under low u conditions a decoupling between the above and within canopy processes developed more in narrow than the wide strips. Then the unstable lower part of the canopy in narrow rows is capped (covered) and thereby decoupling from the above canopy. Therefore, the canopy structure and the buoyancy force from the soil surface are the two variables important to this free convection state for the low windy conditions under IRWH cropping system. In a maize crop with 0.75 m row spacing, Jacobs and Nieveen (1995) described how a free convection state occurs in which turbulence is generated by the relatively warm at the lower part of the canopy. This situation is in agreement with the narrow strips when the bottom portion of the canopy showing higher θv during the late morning and late afternoon hours.

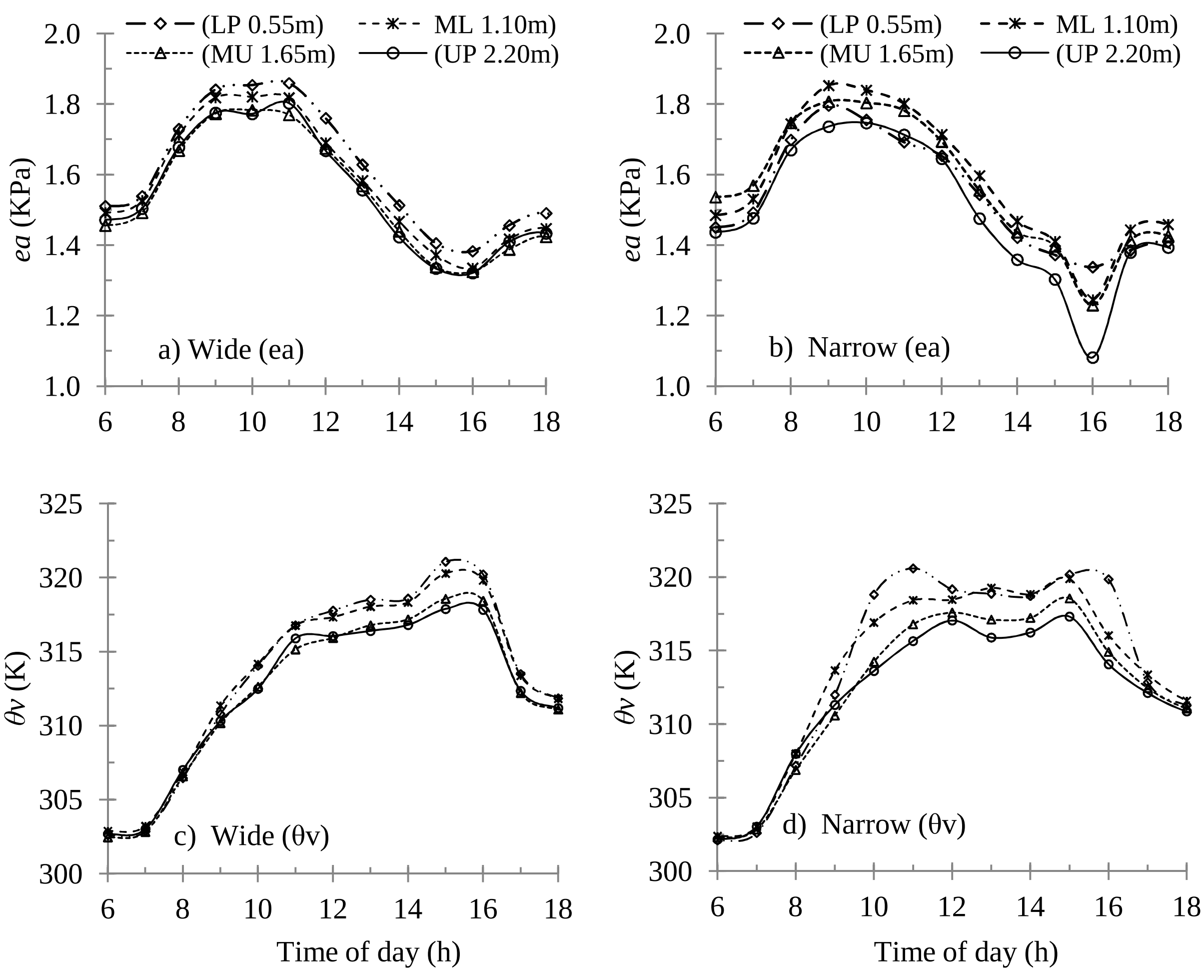


Figure 8.9 Diurnal trend of water vapour pressure (ea) and virtual potential temperatues (θv) at four heights in the narrow and wide at Kenilworth Bainsvlei, 11 Mar., 2009 (80 DAP).

Figures 8.9c&d clearly demonstrate that at morning and midday time the narrow runoffs are slightly warmer than the wide ones but in late afternoon it can be seen that the reverse conditions occurred with the wide rows being a slightly higher θv. So it appears that the plants on the wide runoff strips were heated by the late afternoon sun and retained that heat for a few hours. Therefore, the inversion form of θv at lower canopy (ML) in wide rows is due to the fact that leaves are fully exposed to full sun slanted rays. Consequently, during late afternoon after some hours of exposure to the sun, the wide θv is greater than the narrow rows θv and showed a net radiative loss of energy from the surface during late afternoon time at 16:00 (see Chapter 10). However, in the narrow rows the direct sun hit on the top of the canopy and reflected back some radiative energy, but narrow rows θv remains higher than wide θv around midday. The nocturnal variations or differences in temperature profiles for wide and narrow runoff strips are smaller and often negligible (Appendix 8.3b).

8.4.3 Relationship between profile parameters

In evaluating the characteristics of the profiles within the maize canopy, all the variables *(*u, ea & θv) showed variation in different growth stages and over the course of the day. Moreover, all variables rendered variations on the magnitude of the entity according to the diurnal variations. For example, the nocturnal ea or θv changes are much weaker and smaller relative to daytime, as in the night the air movement is mainly dominated by free convection, whereas during the day a mixed convection is nearly always present in the processes of heat and water vapour exchanges. As most evaporation takes place during the daylight hours, one is more concerned with these times, therefore, the correlation between the variables within the canopy, was investigated for daytime hours (08:00-17:00) only.

During different growth stages different microclimatic and profile characteristics were observed (see section 8.4.2). For example, on a relatively windy day (DAP 47) the diurnal changes of u versus ea and θv versus ea gave good agreement with a second degree polynomial and linear fitting, respectively for both wide and narrow strips. From this regression analysis of the combined data set profiles, the coefficient of determination (R^2) obtained were 0.78 & 0.71 and 0.86 & 0.85 for the wide & narrow RSL treatments for the u versus ea (Fig. 8.10a) and θv versus ea relationships (Fig. 8.10b).

The result from Fig. 8.10a can be expressed as, on both RSL treatments the effect of wind on ea varied at different layers due to the lower removal of momentum from the wind flow is transferred downward. This means that slow moving air flow occurred deep in the lower part of the canopy, but the magnitude of wind speed was different in wide and narrow RSL treatments (as describe in Section 8.3.1). In other words, the lower layer of the plant canopy receives a smaller supply of momentum and removal of ea through transpiration was also lowered due to reduced penetration of radiation in the lower part of the canopy. Moreover, as pointed out in the above section, the sparse canopy structure of row planted maize under IRWH is poorly coupled to the atmosphere. Therefore, in general the effect of u on ea concentration was due to its influence on the resistance of boundary layer and the canopy and soil surface resistance (Ham and Heilman, 1991). This implies that the loss of water vapour through Ev and Es by maize plants and from the soils surface of the basins and runoff strips depends on wind.

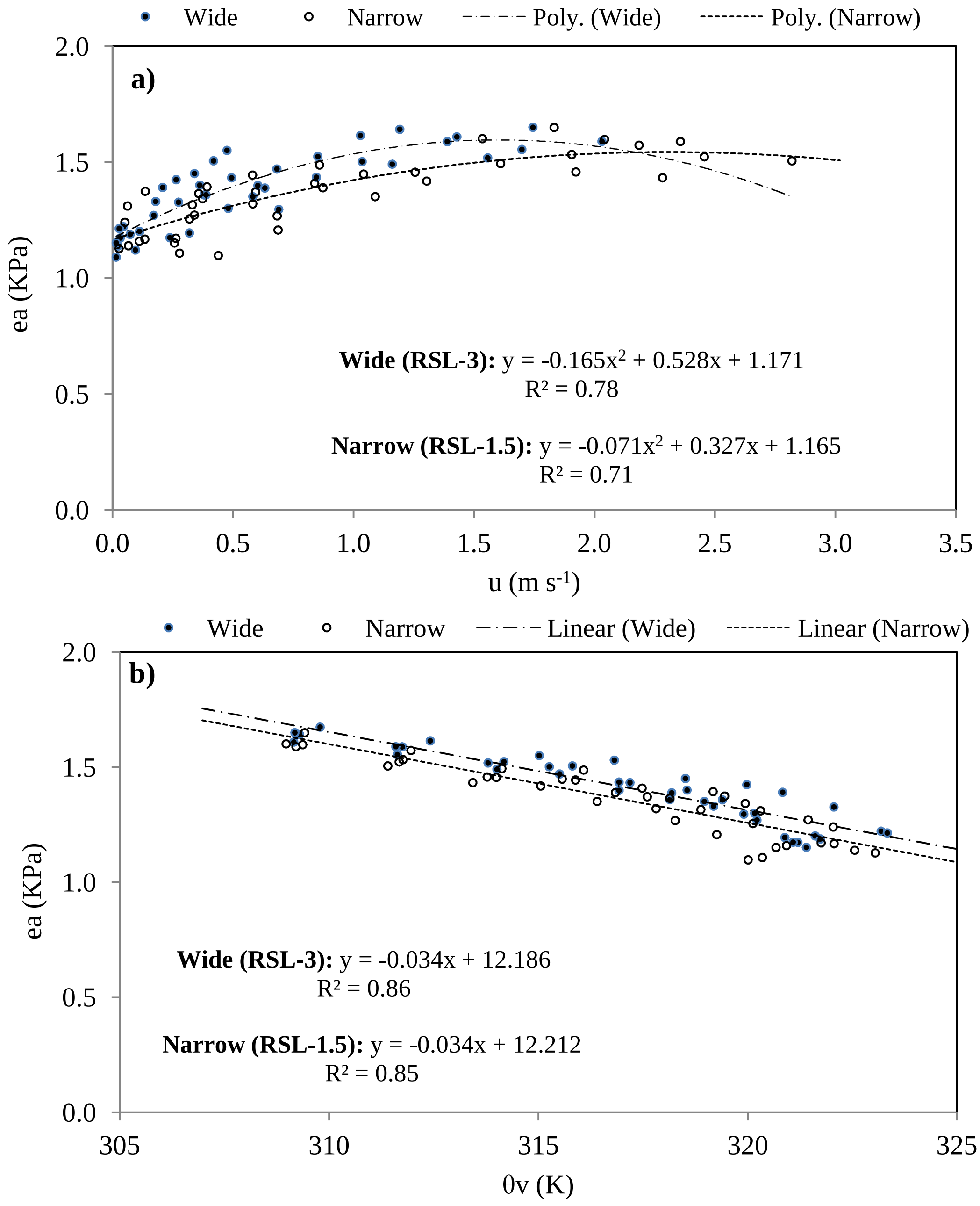


Figure 8.10 Daytime relationship a) for wind speed (u) versus water vapour (ea) and b) for virtual potential temperature (θv) versus ea of all profile measurements (n=40) on 6 Feb., 2009 (47 DAP) on wide and narrow runoff strips.

The Ev and Es (ET) within the canopy increases the ea concentration but it is determined by the magnitude of the wind speed. Thus, Fig 8.10a clearly illustrates that for both RSL treatments with increase in u the concentration of ea within the canopy increases up to a certain level of ea (i.e. about 1.6 KPa), but this plateau was reached at a range of 1.4 - 1.8 m s^{-1} and 2.0 - 2.4 m s^{-1} for wide and narrow RSL treatments. This confirms that the resulting variations in Ev and Es in the wide and narrow tillage of IRWH modify the airflow within the canopy, thus creating gradients in ea. In other words, indirectly Ev and Es rates were affected by the wind speed order of magnitude. So that, the driving force for ET at any RSL is the gradient of ea and the resistance to ET processes is related to wind speed effect on ea concentration within the canopy. This can be explained in sparse planted maize under IRWH as it is possibly referred to via the relationship of u and ea through the evaporative demand and on the drying power of the air within the canopy in both wide and narrow strips. This meant that the wide RSL is faster in response to evaporative demand of the atmosphere and supplying higher drying power of the air compared to narrow RSL treatments.

In the case of the relationships between the profile measurement of θv and ea, it is of interest to find out if the combined four layers within canopy (LP, ML, MU & UP) agree with different criteria based on the windy condition on 47 DAP (Fig. 8.10b). The linear regression line is well fitted with only slightly higher intercept in the wide compared to narrow strips. but there were no significant differences between the wide and narrow strips at $P < 0.05$ significance level. However, both trends showed with an increase in θv the concentration of ea within the canopy decreased sharply. This meant that, the lower θv and higher ea results in a lower rate of transpiration from the plants and limited evaporation from the soil surface. While under hot sunny (higher θv) and windy condition Ev can exceed the rate at which water can be supplied from the soil and hence stomata may close to prevent water losses from the maize plants. However, in general the wind profile within the wide strips causes more eddies compared to narrow strips, and thereby maintains the ea gradients more favourably between the air within the canopy and evaporating surface (plants and soil surface). As a consequence, ET increases dramatically with increase turbulence but only up to critical limit determined by the humidity and temperature within the canopy and of course especially on the available energy (radiation).

To summarize the relationship of climatic variables within the plant canopy in influencing Ev and/or Es under the tillage system of IRWH, the key factor is the movement of air and turbulence that is a function of wind speed and that depends on the length of runoff strips. Increased movement of air within the plant canopy will result in higher ET rate, thus a high wind speed has an implication in the control of ET because wind operates the movement of saturated air in the plant canopy. On the contrary, under weak wind condition the air within the canopy may not move very much, raising the humidity of air around the canopy such that the air tends to become saturated air unless it is replaced by drier air. For example, for the case of low wind conditions (62 DAP), the vertical profiles relationships of both u versus ea and θv versus ea were shown to have poor relationships (Appendix 8.5).

8.5 Conclusion

Very few literature references have been found on the spatial and temporal distribution of weather variable profiles within the crop canopy, and none considering the technique of IRWH. Nevertheless, it should be clear that a comprehensive and good description of Ev and Es processes must necessitate a thorough study of the vertical profiles within plant canopy, in particular during the daylight time. This understanding of vertical profile within canopy improves the formation of an impression for the reason why wind and temperature profiles related to water vapour concentration within the canopy for wide and narrow RSL treatments. Thus, from the results the following main conclusions can be drawn:

i) Growth stage had a pronounced effect on the vertical profile in terms of the magnitude and structure of the parameters within a maize canopy. The existence of inversion increasing ea and θv at UP in the wide runoff canopies is as a result of the wake-generated turbulence in the upper layer of the canopy. It is speculated that this turbulence is higher in wide compared to narrow strips. In a broad sense, the main differences between the water vapour profiles in wide and narrow runoff are the shape of the profiles in the lower and upper part of the canopy. In wide runoff strips lapse conditions extended from lowest measurement level (LP) to the upper middle section (MU) of the canopy and inversion was apparent at the top of the canopy.

ii) Unlike the water vapour profiles, the temperature profiles do not show uniform changes over the course of the day. In most profiles during daytime, the temperature had a slight inversion or lapse in the lower part of the canopy and during nighttime it was close to isothermal conditions due to the fact that canopies trap most of the outgoing long-wave radiation. The main difference observed on the wide runoff area is the temperature inversion at the top (UP) of the canopy during the midday hours and often close to isothermal conditions in the late morning and nighttime. The reason for the extension of temperature inversion into this part of the wide canopy is as result higher air movements compared to narrow strips.

iii) Results showed that, from the relationship of u and ea concentration, ea reached plateau at about 1.6 KPa at a range of wind speed value of 1.4 - 1.8 m s^{-1} and 2.0 - 2.4 m s^{-1} for wide and narrow RSL treatments, respectively. Thus, the Ev and Es within the canopy increased the ea concentration but it was determined by the wind order of magnitude. This indicated that the sparse maize canopy of the wide RSL could supply more drying power of the air in response to atmospheric evaporative demand compared to narrow RSL treatment. This is due to the variation in air flow in wide and narrow runoff strips that would create gradients in ea for ET processes. From the study it was also found that during windy condition with increase of θv the ea concentration within canopy decreases in both runoff strips. Nevertheless the wind profile within the wide strips causes more eddies compared to narrow strips. As a result ET increases dramatically with increase turbulence but depend on the magnitude of humidity and temperature profiles within the canopy.

CHAPTER 9

Profile Characteristics and Water Vapour Pressure Deficit Relations above a Maize Canopy

9.1 Introduction

Understanding of the momentum and heat transfer inside and above the canopy is an essential step to quantify and evaluate the heat and water vapour exchange processes. The assumptions underlying the theory of one dimensional energy exchange can be challenged for a number of circumstances that are of agricultural interest including various tillage systems (Stigter, 2010). For instance, in the system of in-field rainwater harvesting (IRWH) with different arrangements of runoff and basin area, it can be seen that various small-scale processes occur within and above crop canopy. A maize canopy under IRWH acts as a source and/or a sink of heat energy and water vapour. Besides this the air surrounding the crop is always in turbulent motion, which causes efficient mixing and exchanges of heat and water vapour, with the crop surface. Therefore, it is noted that, an understanding of the effects of the vertical profiles of heat and water vapour at canopy level gives a clear indication of the fluxes.

Various experimental measurements have confirmed that horizontal wind speed is strongly sheared at canopy height and attenuates quickly within the canopy (Rosenberg *et al.*, 1983; Allen *et al.*, 1998). The canopy effects are felt from the ground up to canopy height which is described as the roughness sub-layer (Garratt, 1992). A good understanding of vertical profile of horizontal wind speed within and above a plant community is a prerequisite to understanding turbulent transport of water vapour as well as temperature fluctuations within a crop canopy (Arya, 2001; Figuerola and Berliner, 2006). Over time, the mean horizontal wind speed (u) will vary rapidly with height above the ground through the roughness sub-layer, particularly within the plant canopy, due to the effects of drag exerted by the underlying surface (Raupach *et al.*, 1991; Kroon and Bink, 1996). Water vapour and heat fluxes are some of the most important constituents of the atmosphere which also have great biological importance (Ray *et al.,* 2002). The bulk rates of exchange between the canopy and the air flowing over it can be determined by measuring vertical fluxes in that part of the boundary layer.

Within the plant canopy, turbulence is generated from several sources. First, there is solar radiation absorbed by the leaves and soil surface, which warms the surrounding air. The induced buoyancy of warm air leads to the generation of turbulence (Monteith and Unsworth, 1990). Another important factor is frictional resistance to air flow due to the soil surface and vegetative cover (Allen *et al.,* 1998). In the IRWH system, the bare area (runoff strips) between the planting zone (basin) and the next basin is drying out due to a high solar radiative load and can generate plumes of hot air (Figuerola and Berliner, 2006). These plumes may therefore enhance a strong lack of horizontal homogeneity due to the arrangement of basin area and runoff sections in IRWH. On the other hand, within the canopy layers in the basin area, an increase in temperature occurs near the level of maximum leaf area where most of the solar radiation is absorbed. However, in general the highest temperature was observed in the lower and middle lower portion of the canopy for narrow and wide strips, respectively (see. Chapter 8, section 8.3). Thus, the source of semi-homogenous characteristics within the maize canopy under IRWH system is a balance between the processes of energy input by radiation and its redistribution by convection, However, the details of these profiles have not been measured before.

The experimental maize field under IRWH technique was not specially designed for micrometeorological-based studies, however, later it was used to evaluate profile characteristics and relationships. In reality, this was difficult as the IRWH tillage systems are heterogeneous in nature, as the experiment has runoff strips of various sizes alternated with basin areas of maize rows. So the IRWH field, does not meet the ideal conditions for a micrometeorological study, but the purpose was to measure the vertical profile of temperature and VPD both within and above the maize canopy of a typical IRWH system. These micrometeorological measurements will be used to express the heat exchange processes for wet and dry surfaces and air passing over it. The main objectives of the study were:

- to characterize the vertical profiles of temperature (using virtual potential temperature θv), water vapour pressure (ea) and wind speed (u) within and above a maize canopy for dry and wet conditions in wide and narrow runoff strips; and
- to describe the water vapour pressure deficit (VPD) under different atmospheric and soil surface conditions for both wide and narrow runoff strips.

9.2 Materials and methods

9.2.1 Experimental layout

Measurement of profiles and water vapour pressure deficit (VPD) was conducted during the last part of cropping season of 2008/09 from 16 April – 12 May, 2009 (DOY 106 – 132). The main experimental design and treatments were described in Chapter 2, Section 2.2. Detailed descriptions of the site and the layout arrangement of the micrometeorological studies are given in Chapter 2 Section 2.3 and Chapter 8 sections 8.2.1. The detail characteristics of Kenilworth Bainsvlei ecotope are also given in Chapter 2 Section 2.3. Total rainfall received during the first measurement period (DOY 106-121) on wide runoff strip was 9.1 mm, while 21.9 mm was received during second measurement period (DOY 122 - 132) on narrow runoff strip.

9.2.2 Measurements and research approach

From the four RSL treatments in this overall project, only two RSL treatments were selected, *viz.* 3 m and 1.5 m to represent a wide and a narrow runoff strip lengths. The micrometeorology observations were taken over the wide RSL treatment from day of year (DOY) 106 - 121 (first period) and over narrow RSL treatment from DOY 122 - 132 (second period), as sufficient instruments were not available for simultaneous measurements. Within these periods, several measurement days were then selected in order to describe the profiles within the RSL treatments. The criteria for selecting the days were only trends to represent a typical dry or wet day given the prevailing weather condition such as the magnitude of wind speed and diurnal temperature variation (Table 9.1).

Table 9.1 Selected days for profile characterization studies for wide and narrow runoff strips and average day time weather condition (8:00 -18:00) data from automatic weather station

Treat.	Selected days (DOY) & Soil Cond.	RF		T	RH	u	VPD
		(mm)	(DOY)	(^oC)	(%)	(m s^{-1})	(KPa)
Wide	107 Dry	-	-	23.5	25.0	1.8	2.3
	108 Dry	-	-	22.5	30.2	2.6	2.0
	112 Dry &Windy	-	-	17.9	51.0	4.7	1.1
	117 Wet	5.9+1.5	115&116	17.6	39.4	1.2	1.3
Narrow	125 Wet & Windy	6.2	124	16.2	70.7	3.6	0.6
	126 Wet	6.3	125	17.7	65.9	1.9	0.8
	127 Wet	9.2	126	17.4	49.6	2.0	1.1
	131 Dry	-	-	17.1	44.5	2.4	1.2

RF= rainfall, T= temperature, RH= relative humidity, u= wind speed and VPD= vapour pressure deficit.

As the weather conditions are not like a treatment that one can impose during a selected time period, one has to use the weather conditions that occurred naturally during the available measurement period. However, the focus of this study was concentrated on the variations through the diurnal cycle of both day and night. Thus, means of hourly data of each variable (u, θv and ea) were calculated for four time periods each of three hours. The four time periods in the diurnal variation were set-up to represent the morning (8:00 - 10:00), midday to afternoon (12:00 - 14:00), evening time (18:00 - 20:00) and night time (22:00 - 24:00).

9.2.3 Instrumentation

The climatic variables were measured both within canopy (1.8 and 2.1 m) and just above the canopy (2.4, 2.7, 3.0, 3.3 & 3.6 m) up to the reference level (4.5 m). A long mast was firmly attached to a tripod stand and buried deeply to hold the arms and sensors steady at the required height. The average height of the maize canopy (*hc*) at its maximum was 2.2 m. Sensors collected hourly observations of temperature, humidity and wind speed at eight heights of 1.8, 2.1, 2.4, 2.7, 3.0, 3.3, 3.9 and 4.5 m above ground surface (Fig. 9.1).

Figure 9.1 Sensor arrangements in the wide runoff section within and above the maize canopy from 1.8m up to the reference height of 4.5 m on 07 April, 2009.

Measurements performed at eight levels within and above the maize canopy were as follows:

- wind speed was measured using three-cup wheel Sentry anemometers (Model 03001) with stalling speed of about 0.15m s^{-1};

- temperature and humidity were monitored using HMP50 temperature and relative humidity probe, which contains PRT and Vaisala-INTERCAP sensors for temperature and relative humidity respectively (Model HMP50 Campbell Scientific, 1994 USA);
- HMP50 sensors were housed inside white plate radiation shields (41303-5A Model);
- all micrometeorological data were recorded on a CR1000X data logger (Campbell Scientific, 1994) every 5 min. and averaged over one hour for storage;
- the datalogger used for these measurements was programmed to periodically save the data;
- instruments were frequently checked and
- data was regularly downloaded with some overlap from the previous download.

9.2.4 Data handling and analysis

All data handling and processing followed the same procedure as described in Chapter 8 Section 8.3.3. The data analysis was for diurnal variations and to compare different weather conditions of dry, wet, windy and rainy days. Air temperature and relative humidity were used to calculate the vapour pressure deficit (VPD) for each layer in the profile. Furthermore, evaluation of profiles and vapour pressure deficit (VPD) were performed to demonstrate the atmospheric driving forces for the latent heat fluxes. Under relatively strong windy conditions, the dependence of VPD and temperature on wind speed magnitudes was illustrated using a simple regression for wide and narrow runoff strips.

9.2.5 Statistical analysis

From the recorded hourly climatic variables (ea, θv and u), a statistical analysis was done on results of three-hour means for the effect of time of day (morning, midday, evening and nighttime) and on 8 profile heights of measurements (z) on selected days during first and second periods of measurement. The statistical package used was the software SAS 9.1.3 for Windows (SAS Inst. Inc., 2006). In the analysis, replicated three times a two way factorial Randomized Complete Design (RCD) was adopted. Means and LSD for the main treatment effects were computed and presented in Appendix 9.1 and 9.2. Empirical relationships between climatic variables were derived using regression procedures.

9.3 Results and discussion

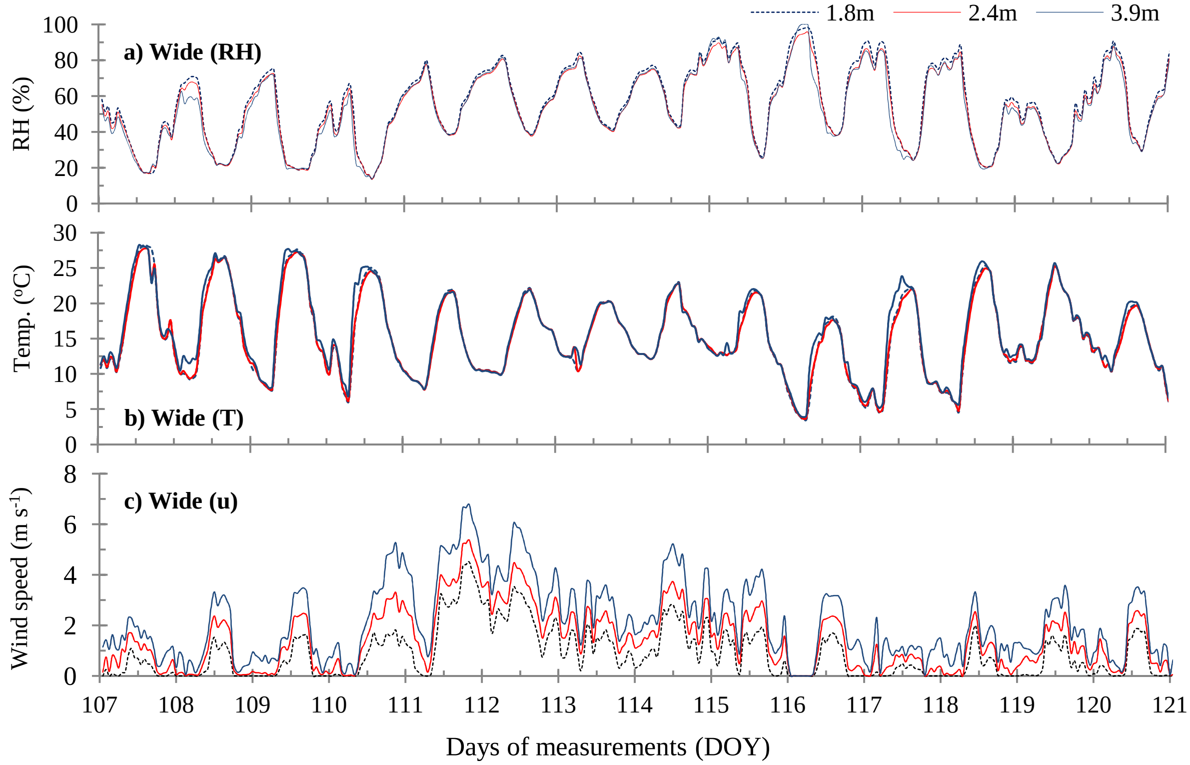
9.3.1 Climatic variables within and above canopy

The main characteristics of the measured data during the two measurement periods (runs) are plotted to give a general impression of the trends at different exposures: within canopy (1.8 m), immediate above the canopy (2.4 m) and at reference level of 3.9 m above the ground (Fig. 9.2).

In general, from the data of relative humidity, RH (Fig. 9.2a & d), it can be seen that during the first run (wide RSL), minimum RH (midday value) increases slightly and decreases again but not to such a low level. During the second run (narrow RSL), the minimum RH decreases after it reached a maximum on DOY 126 following the rainfall. The RH had small differences according to the level, but within canopy measurements renders relatively higher values compared to the reference level measurements as will be seen later. However, for air temperature data (T) the highest values appear at the reference level (Fig. 9.2b & e). In general, in both RSL the trend of T values moves in the form of 3-4 day periods when it fluctuates at about the same level, in particular in the case of the second run over the narrow RSL. Moreover in the first run measurements, RH has a narrower daily range and appears to increase from DOY 107-117 while minimum temperature decreases, which represents the condition on rainy wet days and to some extent it reverses from DOY 118-120.

Winds were from north (N) and northwest (NW), and remain weak during most of the measurement period with an average of less than 2 m s^{-1} and rarely exceed 4 m s^{-1} (Fig. 9.2c & f). On days 112 and 125 DOY the wind was quite strong during daytime and approached 7 m s^{-1}. However, it exhibits a clear diurnal cycle with minimum and maximum values at around midnight and noon respectively, while the strongest wind was observed at reference level above ground. The implication of these variations in the measured data of RH, T and u at different levels helps one to form a general picture and thus better understanding the variation in heat and water exchange processes within and above canopy for wide and narrow RSL arrangements. One must continue to bear in mind that it is not possible to 'control' the weather, but one has to select specific day to 'use' to describe the phenomenon occurring within the range of natural variation during the measurement period.

First period measurement (run)



Second period measurement (run)

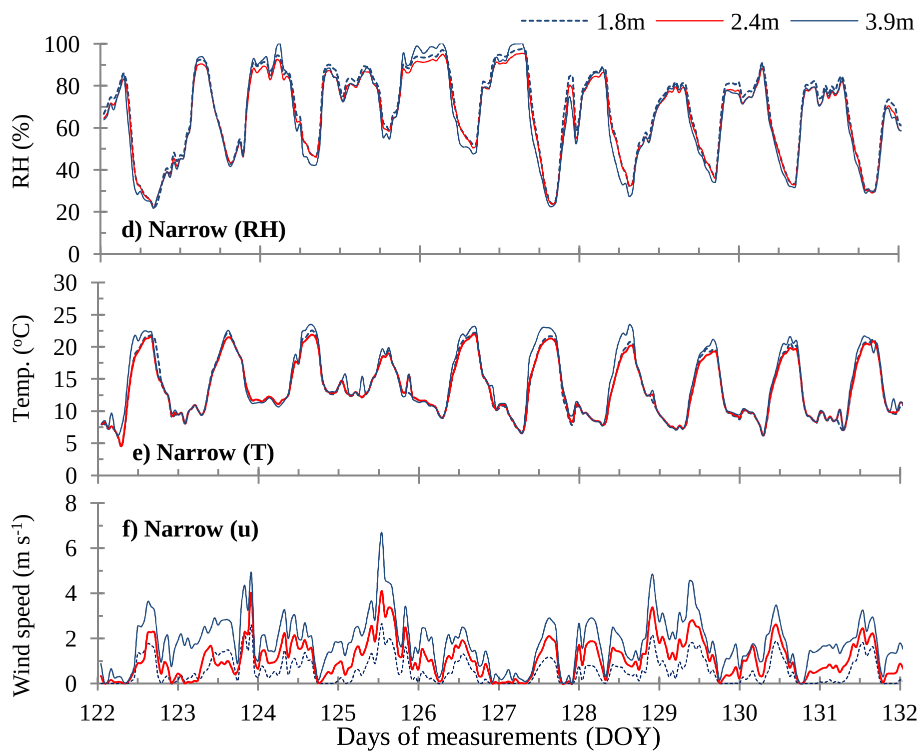


Figure 9.2 Measured values of relative humidity, RH (a & d), air temperature, T (b & e) and wind speed, u (c & f) within the canopy (1.8 m), above the canopy (2.4 m) and at reference level (3.9 m) above the ground.

9.3.2 Vertical wind speed profiles

The profiles of horizontal wind speed within and above maize canopy for diurnal variations showed that u increased with height on both dry and wet days (Fig. 9.3). The diurnal change over the wide RSL, on a dry day (DOY 107) shows u was higher in the morning than afternoon hours and with a rapid increase from the level just above the canopy to 3.9 m height, and then remained almost constant above that level. The lowest u was reached in the evening hours and it remained quite calm throughout the night time (Fig. 9.3a). The observed data on a day after rain (DOY 117) also shows that in both morning and around midday, there were lower winds, with the highest wind being observed around noon only up to 1.5 times canopy height and decreasing very slightly above that level, and then during the night time, the wind increased sharply with height from that level (1.5*hc*) (Fig. 9.3b) as was often seen.

From Fig 9.3c&d for narrow runoff strips, the wind speed profiles through the diurnal course of day show similar trends but with different magnitudes on dry (DOY 131) and wet days (DOY 127). For example, at around midday (12:00 - 14:00) the minimum wind speed profile observed is within the canopy with values 0.9 and 1.5 m s^{-1} on wet and dry days respectively and the highest wind speed was measured at 4.5 m height with 2.3 and 3.0 m s^{-1}. However, on a dry day (DOY 131) during morning hours the wind speed ceases to increase just above the canopy (2.2 m) and then increased at 1.5*hc* (3.3 m) level but decreased sharply above 4 m from the ground (Fig. 9.3d). This indicates a slight “bulge” formation in the equilibrium layer (just above the canopy) and being more pronounced in the thermal boundary layer (at 1.5*hc*) under the local advection conditions. Very small “bulge” phenomena also occurred in a wide RSL during the morning hours and often extended to around the midday (Fig. 9.2a & b) but they are not as prominent as DOY 131.

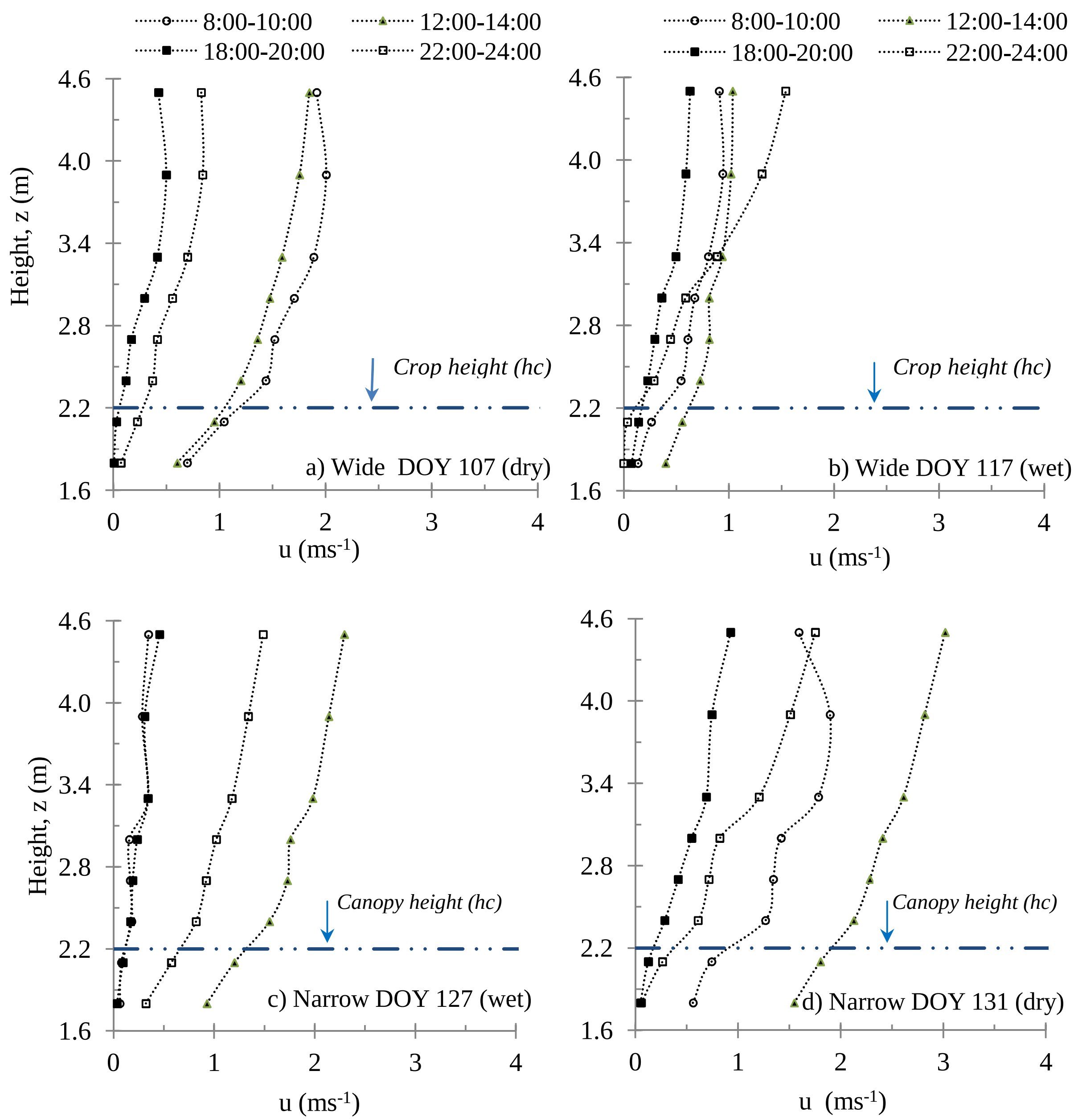


Figure 9.3 Observed wind speed profiles within and above canopy on wide runoff strips on dry (DOY 107) and wet (DOY 117) days and on a narrow runoff strips on dry (DOY 131) and wet (DOY 127) days at Kenilworth on 17&27April and 7&11May, 2009. (LSD value between periods: DOY 107 = 0.206 m s^{-1}, DOY 117 = 0.150 m s^{-1}, DOY 127 = 0.323 m s^{-1} & DOY 131 = 0.198 m s^{-1})

The wide bare runoff strips between adjacent rows are dry and due to high incident solar radiation the soil temperatures may reach very high values and thus generate plumes of hot air. These plumes may therefore enhance the strong horizontal lack of homogeneity due to the structure of row crops especially with wide runoff strips. With dry bare soil between adjacent plant rows, Figuerola and Berliner (2006) described the resultant local advective lowering of the upper boundary layer of the internal boundary layer and its equilibrium layer as a common phenomenon. While the incomplete cover of the plants and the associated plumes from the bottom of the canopy would lead to an increase in the height of the lower boundary layer (Prueger *et al.*, 1996; Figuerola and Berliner, 2006). Thus, the consideration of the presence of local advection within the incomplete canopy cover of the IRWH tillage system was a crucial factor in estimation of water movement or in other words crop evapotranspiration in semi-arid areas. This implies that, in IRWH tillage systems the two important factors having high complexity for evaluating evapotranspiration are: the local advection and high temperatures of the bare soil between adjacent plant rows. Another two days (DOY 112 & 125) both with common strong wind conditions but with different weather regimes have been selected for the vertical profile interpretations (Fig. 9.4). On both days, the maximum mean wind was observed up to nearly 6.0 m s^{-1} around midday time. The wind is stronger on wide runoff strip on day 112 but the temperature only reached about 22.3^{o}C. However, the magnitude of the wind was different within the canopy, being lower on the later rainy day (DOY 125) on the narrow runoff, with values below 1.5 m s^{-1} during 3 of the time periods (Fig. 9.4b).

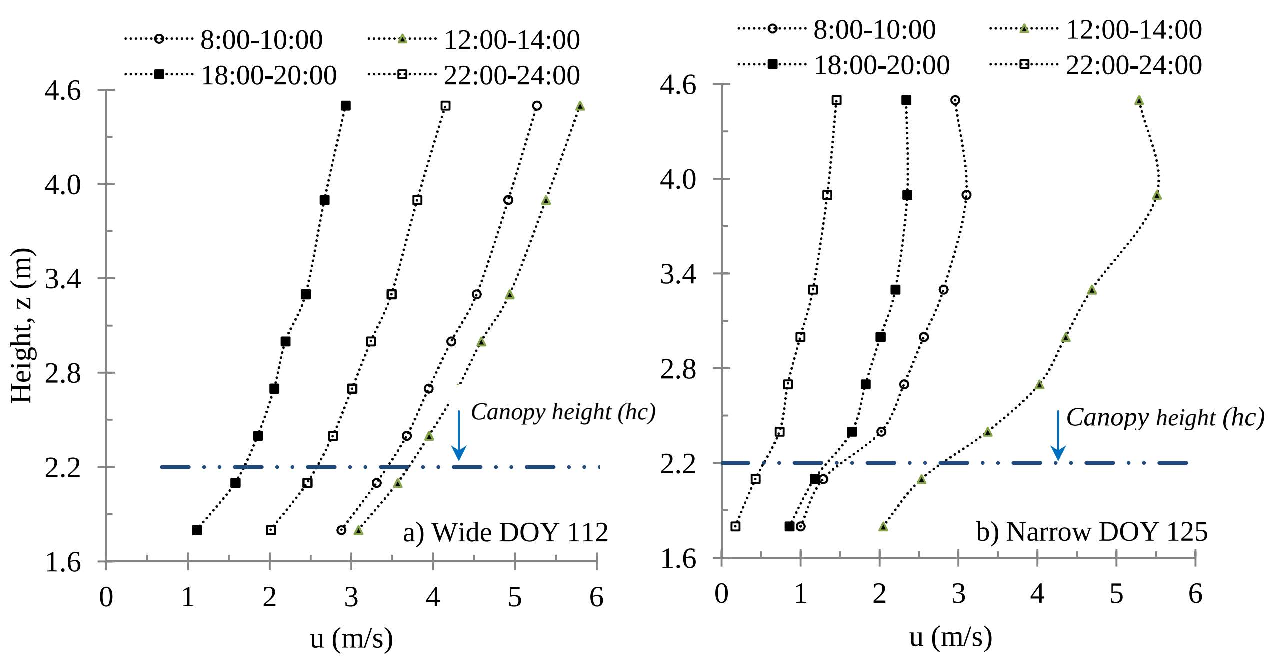


Figure 9.4 Observed wind speed profiles within and above canopy on narrow runoff strip on a dry day (112 DOY) and on wide on a wet day (125 DOY) at Kenilworth on 22 April and 5 May, 2009. (LSD value between periods: DOY 112 = 0.335 m s^{-1} & DOY 125 = 0.397 m s^{-1})

On both these days (wide and narrow RSL) the wind speed increased from the morning into the afternoon (Fig. 9.4). During this midday period, the highest wind speed value was at reference level (4.5 ≅ 2*hc*) reaching 5.8 ±0.26 m s^{-1} and the lowest measured value was within the canopy with 2.1 ± 0.27 m s^{-1} on both wide and narrow strips. Stull (1991) described a diurnal pattern in which the wind speed increases sharply after sunrise, attains a broad maximum in the early afternoon and again decreases sharply near sunset. Figs. 9.4a&b show the typical profile of wind speed in the case of weak turbulent mixing, while the wind speed increases slightly with height above the ground, it moved smoothly towards neutral conditions during the evening and night time. However, the increase in wind speed in the equilibrium and thermal boundary layers (2.4 - 3.9 m) during morning and around midday is as a result of more rapid and efficient transfer of momentum from above the canopy through an evolving unstable or convective boundary layer, during wet periods over the narrow runoff strip (Fig. 9.4b). Moreover considerable effect of advective conditions was also expected during a typical day time under wet conditions (DOY 125) (Fig. 9.4b). Therefore, from these vertical wind profiles, the particular importance of making measurements at specific height intervals above wide and narrow RSL and under different weather conditions (wet and dry / windy and calm conditions) can be seen.

9.3.3 Virtual potential temperature profiles

The magnitude of the variables and thermal stability conditions depend on the canopy structures and the prevailing weather conditions. Hence, some differences in virtual potential temperatures (θv) are expected between the wide and narrow RSL (Fig. 9.5). From the observed θv 3-hourly means, during the course of the day, it was seen that the profiles of θv within the canopy in wide RSL (Fig. 9.5a&b) were more stable or near neutral compared to the profiles in narrow runoff (Fig. 9.5c&d). These graphs represent the dry and wet conditions during the measurement period.

From Fig. 9.5a the profiles clearly demonstrate near neutral stratified conditions, so that the vertical turbulences in wide runoff strips was suppressed compared to the narrow runoff strips. The highest temperature occurs at height of 3.3 m in wide and had increased by 2-3 K on the dry day and 5-6 K on the wet day. Fig. 9.5a-d illustrate that the nocturnal profile was under stable conditions during evening and night time throughout the profile on both dry and wet days. This condition was stable until the moment before sunrise when lowering of temperatures occurs, where the θv profiles are characterized by slightly nocturnal inversions, produced as a result of radiative cooling of the surface within the canopy.

Shortly after late morning (midday and afternoon), moderate to extremely unstable conditions were observed on wide runoff strips on both days of dry and wet conditions (Fig 9.5a & b). The possible reason for unstable condition during the day (Fig. 9.5b) is due to the surface heating that leads to an upward exchange of sensible heat and subsequent warming of the lowest layer above the canopy (z=2.4 m), which is probably due to the vertical convergence of the eddy heat fluxes. Thereafter, the heat exchange processes progressively deteriorated and the night time inversion developed from below to just above the canopy and was replaced with an unstable convective layer between heights of 2.4 and 3.9 m.

Under wet conditions (after rainy day) in the morning hours (8:00 - 10:00), Fig. 9.5b demonstrated that in the lowest air layer just above the crop canopy the layer grows rapidly at first in response to heating from below and its growth continued throughout the day. However, at all levels the increase in θv from 8:00 – 10:00 to 12:00 – 14;00 was higher under dry (9-10 K) compared to wet condition (6-8 K). During dry days (Fig. 9.5a) the growth of the mixing layer was very weak during the daytime and immediately following the transition period to evening, when the sensible heat at the surface changed sign and the unstable conditions suddenly collapsed and were replaced by a shallower stable boundary layer. According to Fig. 9.5 this layer was stratified between 3.3 – 3.9 m height.

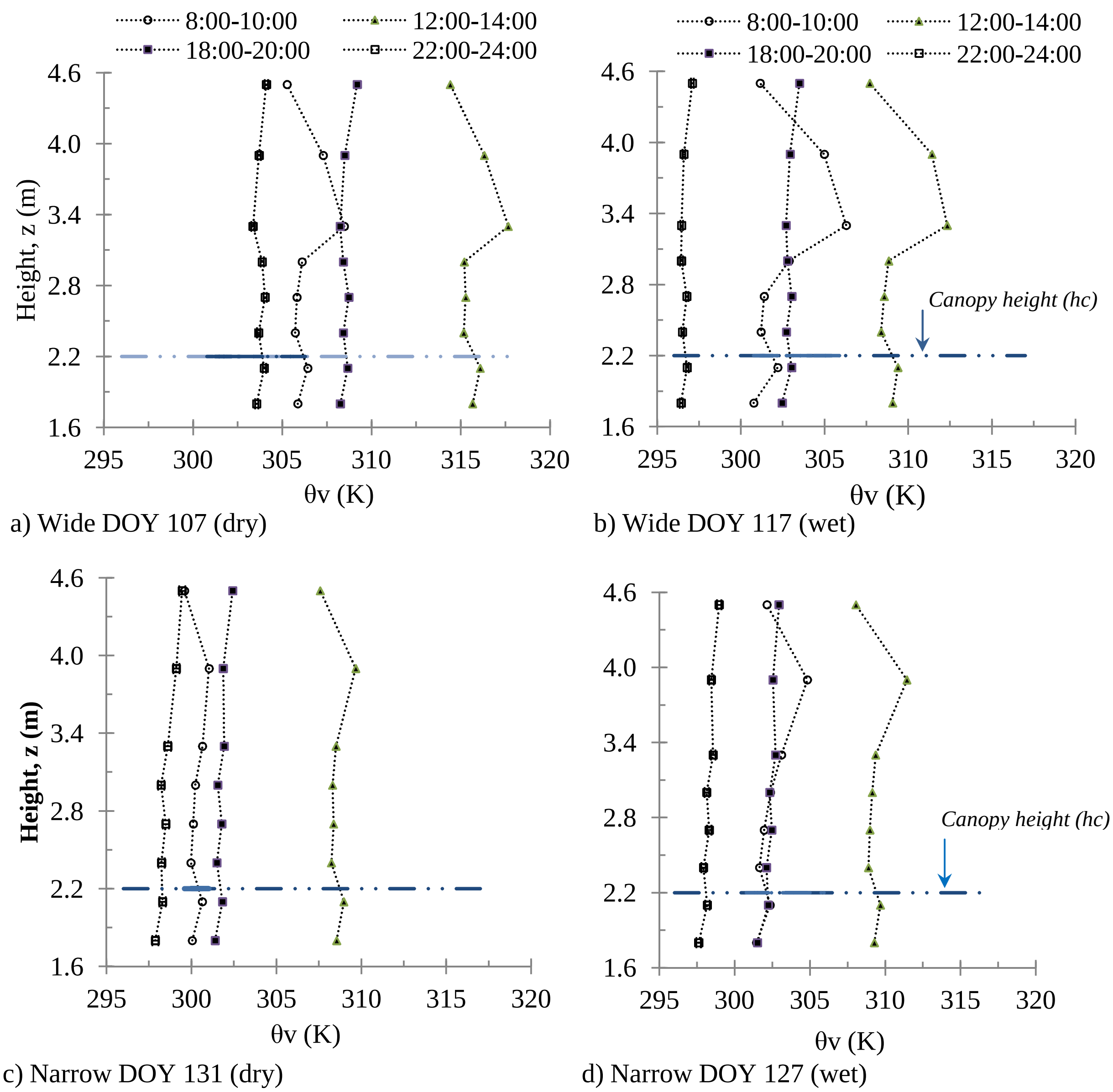


Figure 9.5 Calculated virtual potential temperature profiles within and above canopy on a wide runoff strip for dry (107 DOY) and wet (DOY 117) days and on narrow runoff strip for dry (DOY 131) and wet (DOY 127) days at Kenilworth on Kenilworth on 17&27April and 7&11May, 2009. (LSD value between periods: DOY 107 = 1.77, DOY 117 = 1.677 K, DOY 127 = 1.563 K & DOY 131 = 1.690 K)

On the narrow strips, the highest temperature occurred at 3.9 m height and it was never more than 3 K above the rest of the profile (Fig. 9.5c&d) during the morning and midday periods. Whereas the lowest θv was observed at the highest reference level of 4.5 m, but within the canopy level (1.8 m) for all periods θv had higher values than just above the canopy and up to 3.3 m above the ground. Nevertheless, the most important thing in aerodynamic method is the consideration of the profiles just above the canopy and at the reference level. With this in mind, the more unstable conditions existed around midday time in both wide and narrow strips with gradient of about 0.6 – 0.8 K on the dry day and 0.7 – 0.8 K for wet soil conditions. In all cases, the stable conditions developed progressively during late afternoon and evening time (Fig. 9a-d).

Therefore from the profiles, daytime unstable conditions (convective boundary layer) had three features or a layered structure: one was the surface layer, where θv decreased with height within this shallow layer, and the turbulence is generated by wind shear and buoyancy. This layer started from just above the canopy stretching to between 2.2 and 2.4 m height. The second layer is a mixed layer, in which θv remained more or less uniform and comprised the bulk convective transfer layer. This layer was dominated by buoyancy-generated turbulence except during morning and evening transition hours, when shear effects also became important. As stated by Figuerola and Berliner (2006), there was a third layer above the mixed layer, being a shallow transition layer in which θv increased with height and the turbulence started to decrease with height. Thus, from the above profile description, the height of inversion can be used as an approximation of the mixed layer for the thermal internal boundary layer height above the crop canopy in maize crop under IRWH system.

During windy days (Fig. 9.6a) and rainy days (Fig. 9.6b&c), one often observed irregular profile structures. For instance on a windy day the convective layer in the thermal internal boundary layer above the crop canopy was lowered to 2.7 - 3.0 m height. This was because the strong wind shears may generate some intermittent and sporadic turbulence which is not connected to the surface boundary layer. During calm or with weak winds and surface heating, a thermal mixing layer developed only around midday, while a neutral situation was evolved during night time and morning hours. This situation was also illustrated in Fig. 9.5c under moderate windy conditions.

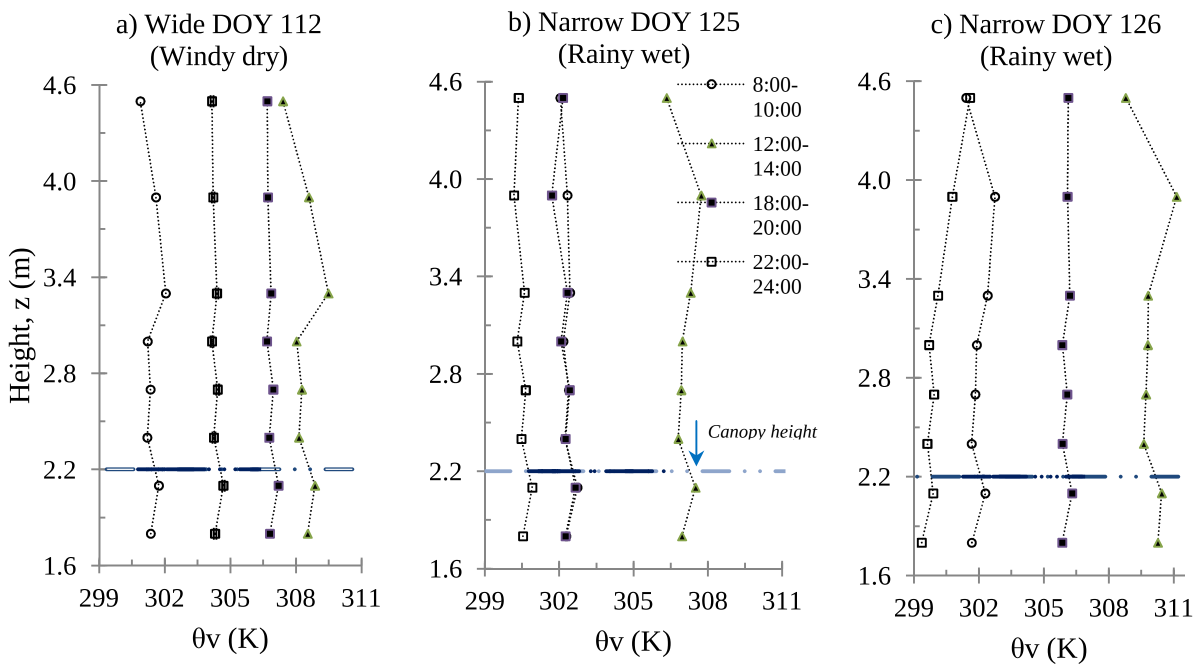


Figure 9.6 Calculated virtual potential temperature profiles within and above canopy for windy days on a wide runoff strip on dry day (112 DOY) and on narrow runoff strip (DOY 125 &126) on rainy wet days at Kenilworth on 22Apr. and 5&6May, 2009). (LSD value between periods: DOY 112 = 0.926 K, DOY 125 = 0.560 K, DOY 126 = 0.323 K & DOY 131 = 1.167 K)

However as illustrate in Fig. 9.6b, with stronger winds but on a relatively cold day, with some showers during the daytime (DOY 125), the mechanical effect of the canopy appears to be increased and consequently dominates the thermal effect above the canopy. This implies that the wind speed decreases as approaching the crop rows and the lowering in wind speed with the surface drug or shear stress increases and the turbulence intensities increase within the canopy. Perhaps the most dramatic change in the thermal internal boundary layer occurs when stable stratified air flow over the cold canopy surface encounters much warmer air within the canopy (z=2.1 m) relative to the air above canopy (z=2.4 m and above). Conversely, if the θv differences between the lower layer (z=1.8 m or 2.4 m) and upper layer (z=3.3 m and above) were fairly large the thermal boundary layer developing over the warmer surface would most likely be very unstable or convective (Fig. 9.6c).

9.3.4 Vertical water vapour pressure profiles

Observed vertical measurements of water vapour pressure (ea) for the same period and positions as the θv profiles were also plotted against the vertical height to show the profile and diurnal variations. On a dry day (DOY 107), ea was higher within the canopy at both heights (z=1.8 & 2.1 m) compared to that measured near the top of the canopy (z=2.4 & 2.7 m height), due to the water vapour released by transpiring leaves within the crop (Fig. 9.7a). Above this level (z ≥ 3.0 m) ea responded to the mixed layer of the thermal boundary layer, so ea profile was first lapse then had inverted.

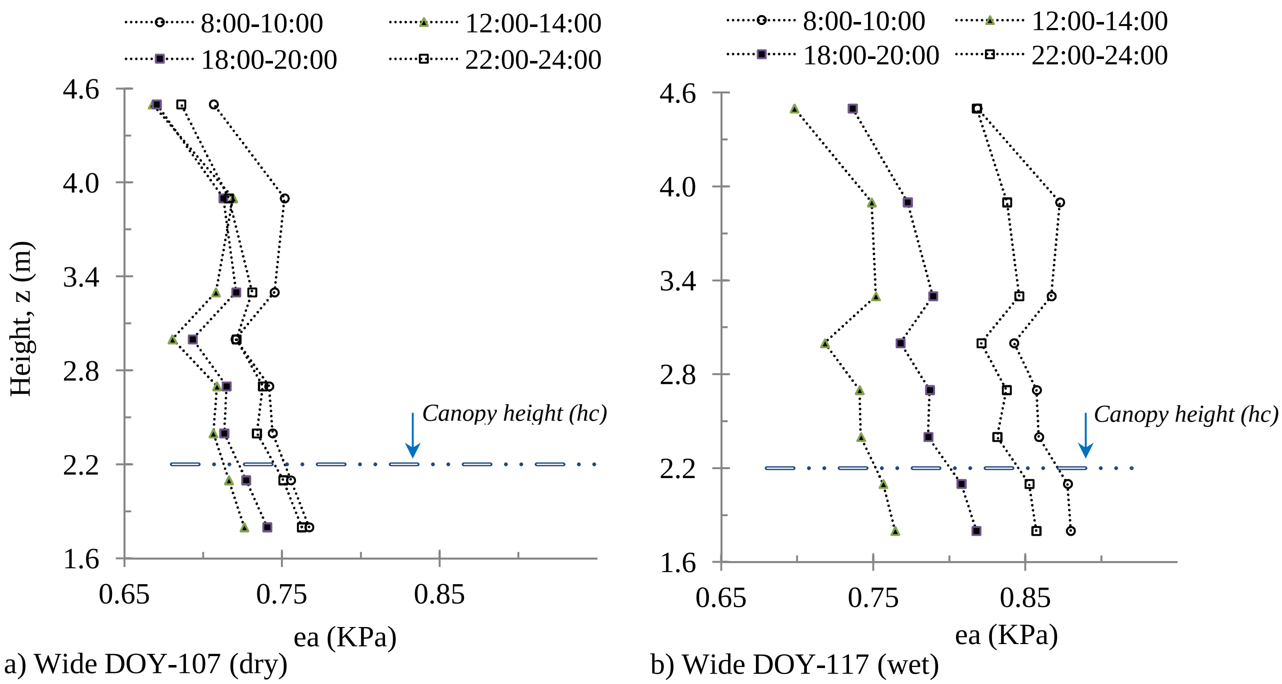


Figure 9.7 Observed water vapour pressure (ea) profiles within and above canopy on a wide runoff strip on dry (DOY 107) and wet (DOY 117) days at Kenilworth 17&27 Apr., 2009. (LSD value between periods: DOY 107 = 0.026 KPa & DOY 117 = 0.027 KPa)

In Fig. 9.7b, on a day after rain (DOY117) with a wet surface condition, the development of ea profile was similar to those shown in Fig. 9.7 for a dry day. However, the magnitude of ea on DOY 117 was higher for each period due to the more freely available water from the wet surfaces throughout the 24 hour measurement period. During all periods of that day, ea profile showed higher values at a level within the canopy (1.8 m) where the upper portion of the canopy was a source of heat and transpiration. Above this level inversions were present up to 3.0 m height and again a lapse condition continued up to highest reference level (4.5 m). During a dry day the change of ea with height was of about a similar magnitude (0.06 KPa). This indicates that the effectiveness of vapour removal increased with increasing day time temperature. This implies that as the day progresses with increasing evaporation or transpiration, the water vapour concentration lowered during a typical daytime (around midday) with a larger VPD as the driving force. However, during night time with low temperatures, the reverse conditions exist with higher RH with a smaller driving force for evapotranspiration. During the wet day (DOY 117), the data showed ea profile goes sharply lapse, but gradient of the profile remained lower due to a cooler temperature (17^{o}C) and relatively higher humidity (40%) in daytime and thus experienced less of a driving force (Fig. 9.7b).

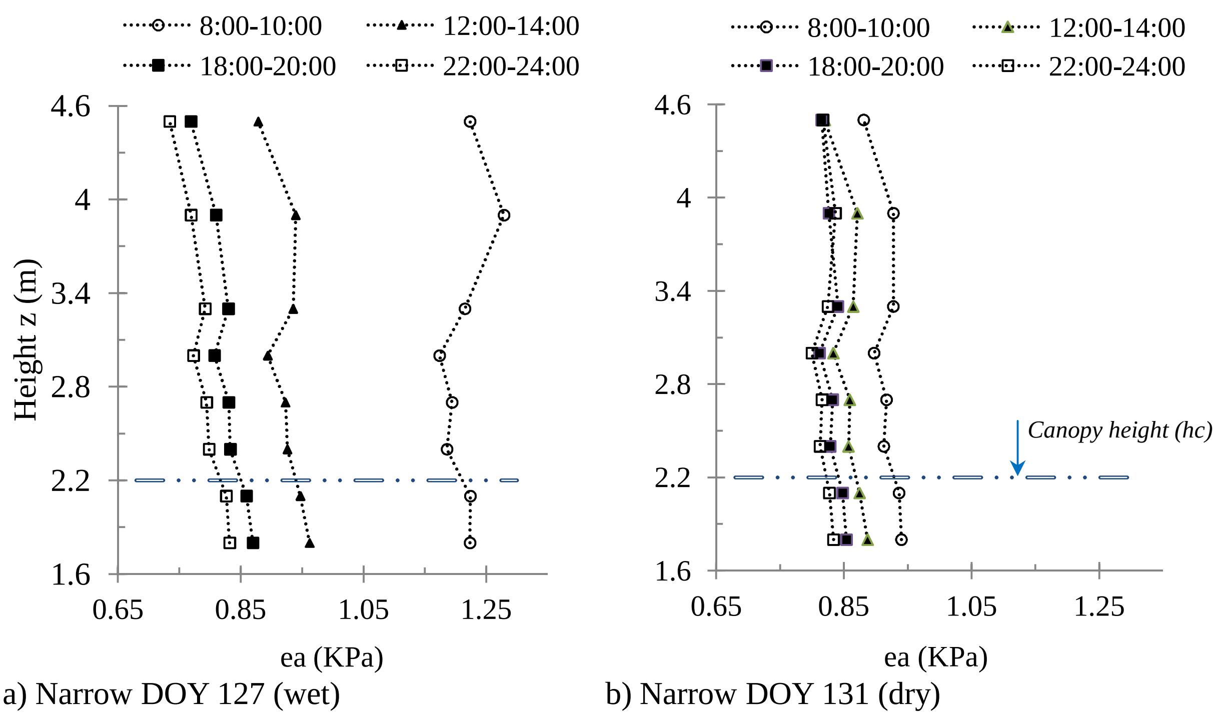


Figure 9.8 Observed water vapour pressure (*ea*) profiles within and above canopy on a narrow runoff strip on dry (131 DOY) and wet (127 DOY) days at Kenilworth on 7 &11May, 2009. (LSD value between periods: DOY 127 = 0.063 KPa & DOY 131 = 0.040 KPa).

The values of ea were higher during the day just after receiving 9.2 mm rain (DOY 127), than on previous days (not shown) or subsequent dry days (e.g. DOY 131), thus one expected a lower evaporation rate. These ea values were also influenced by both the diurnal variation in temperature and prevailing wind conditions (as indicated in Fig 9.1, 9.3 & 9.5). On the dry days, there was much less variation in ea comparing day and night than when the surfaces are wet following rain on either wide or narrow runoff treatments, however the magnitude of the differences was larger on the narrow treatments (up to 0.4 KPa) as much more rain had been received at that time.

On the cold windy day, after a long dry period, there was little water to evaporate and the differences throughout the day were of the order of 0.05 KPa similar to the other dry days (Fig. 9.7 & 9.9). On the rainy day, the ea during midday and the afternoon were higher than those during the morning and the night, due to the rain increasing the amount of freely available water, to maintain the atmosphere nearly saturated (Fig. 9.9). From the previous temperature data (Fig. 9.6) one saw that there was little to no change in the temperature from within the crop up to the highest measurement level at all times during the day and night. So these differences in ea were due to the presence of additional moisture from the rainfall. The generally higher concentration of water vapour (> 0.115 KPa) throughout the day combined with rapid cooling during the evening hours (Fig. 9.6) would have caused much condensation of dew after the rain had stopped. Evaporation from the surfaces was low, as expected, due to the atmosphere being almost saturated throughout the rain periods on that day

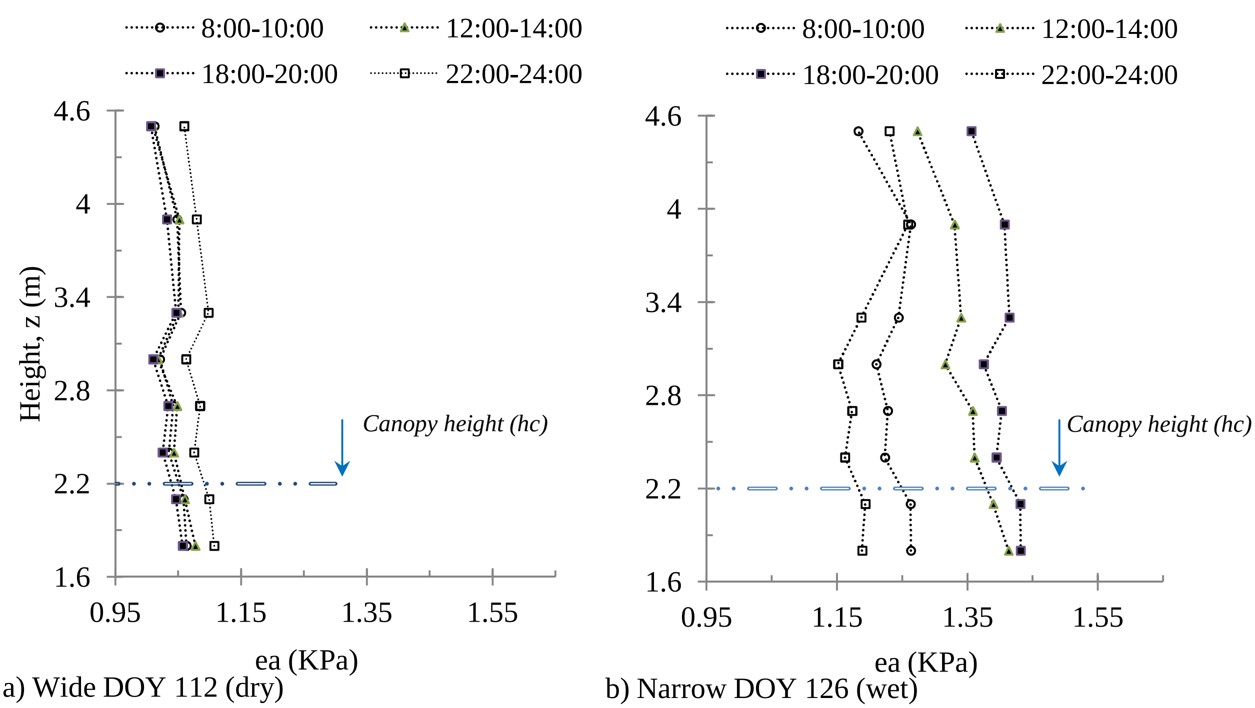


Figure 9.9 Observed water vapour pressure (*ea*) profiles within and above canopy on a narrow runoff strip on dry (112 DOY) and wet (126 DOY) days in Kenilworth 11Apr. & 6May, 2009). (LSD value between periods: DOY 112 = 0.008 KPa & DOY 126 = 0.031 KPa).

There were apparent similarities in the thermal internal boundary layer across all treatments, such that the heights for the surface layers could be determined and are illustrated in a schematic transect constructed from the profile measurement made over the IRWH field of maize (Fig 9.10).

Nevertheless, on days with different conditions, dry / wet / windy / rainy, the advection across wide and narrow varied and was also dependent on wind conditions. From the features of the θv and ea profiles, the mixing layer in the thermal internal boundary layer was typically at the height just above the canopy about 1.5*hc* (2.4 - 3.3 m) and above this there was a shallow isothermal transition layer (3.3 - 3.9 m or 4.5 m). In addition the analysis of the profiles demonstrated that the diurnal variations of moisture content and temperatures (ea and θv) were also related the wind speed and turbulence at each locality and their position in the thermal internal boundary layer under local advection, for the IRWH maize system.

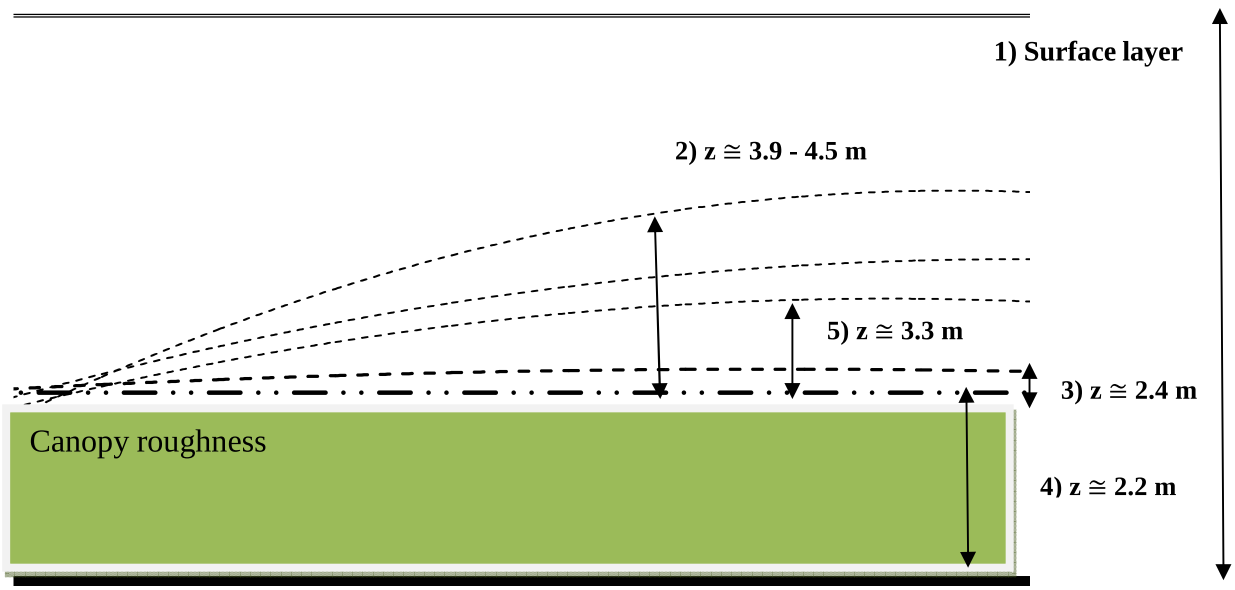


Figure 9.10 The schematic diagram of boundary layer based on profile measurements for a maize canopy under IRWH 1) the surface layer, 2) internal boundary layer, 3) equilibrium layer and 4) canopy roughness layer 5) thermal internal boundary layer under local advection conditions.

Therefore several arguments have been put forward to explain the anomaly of flux gradient relationships for different profile measurement made in wide and narrow runoff strip lengths. However, in the aerodynamic method for the estimation of energy balance components, the most important step is to consider an imaginary plane located above the canopy within the surface layer. According to Rana and Katerji (2000) and Prueger *et al.* (1996), the aerodynamic method has to be applied at heights that are larger than the canopy roughness length and smaller than the boundary layer depth. Thus in the present study of profiles with a maize crop of height (*hc*) 2.2 m the two heights for the aerodynamic method are considered: just above the canopy 2.4 m and at the highest reference level 4.5 m of the internal boundary layer. Savage *et al.* (1997) and Jacobs *et* *al.* (1992) also described the ‘internal boundary layer’ as being of most interesting in crop micrometeorology studies, which was also defined by Brutsaert (1982) as the region of the atmosphere above crop canopies affected by step changes in the surface conditions.

9.3.5 Water vapour pressure deficit relations

Both dry and wet conditions and rainy and windy days showed a similarity for the diurnal profiles but differ in the magnitude of the driving force for evaporation that could exist in a particular period. Thus, in order to elucidate this, vapour pressure deficit (VPD) was calculated and compared through the diurnal variations for both wide and narrow runoff strips (Fig. 9.11). VPD values on all treatments were low early in the morning and then increased as solar radiation and temperature progressively increased throughout the daylight hours and then sharply declined between about 17:00 and 19:00 (Fig. 9.11). However, at approximately 8:00am all the profiles in dry and wet begun to differ and maintained those differences throughout the daytime until the late afternoon sudden decline. The VPD on the wide strips, during the period of 10:00 - 18:00, were between 1.5 and 3.2 KPa at reference height of 3.9 m from the ground and between 0.5 and 2.2 KPa on the narrow strips. This would indicate that on the wide strips the wind was able to replace the air between the rows and thus maintain a higher driving force for evaporation. VPD within and just above the canopy (1.8 and 2.4 m height) showed slightly lower values compared to the reference level but late in the afternoon the whole profile was more uniform (Fig. 9.11). Conversely, on the wet day (DOY 117) the VPD within the canopy did not increase so rapidly in the period from 9:00 - 15:00 hours at the reference level (Fig. 9.11b), that stretched between 0.5 - 2.0 KPa and declined in the late afternoon.

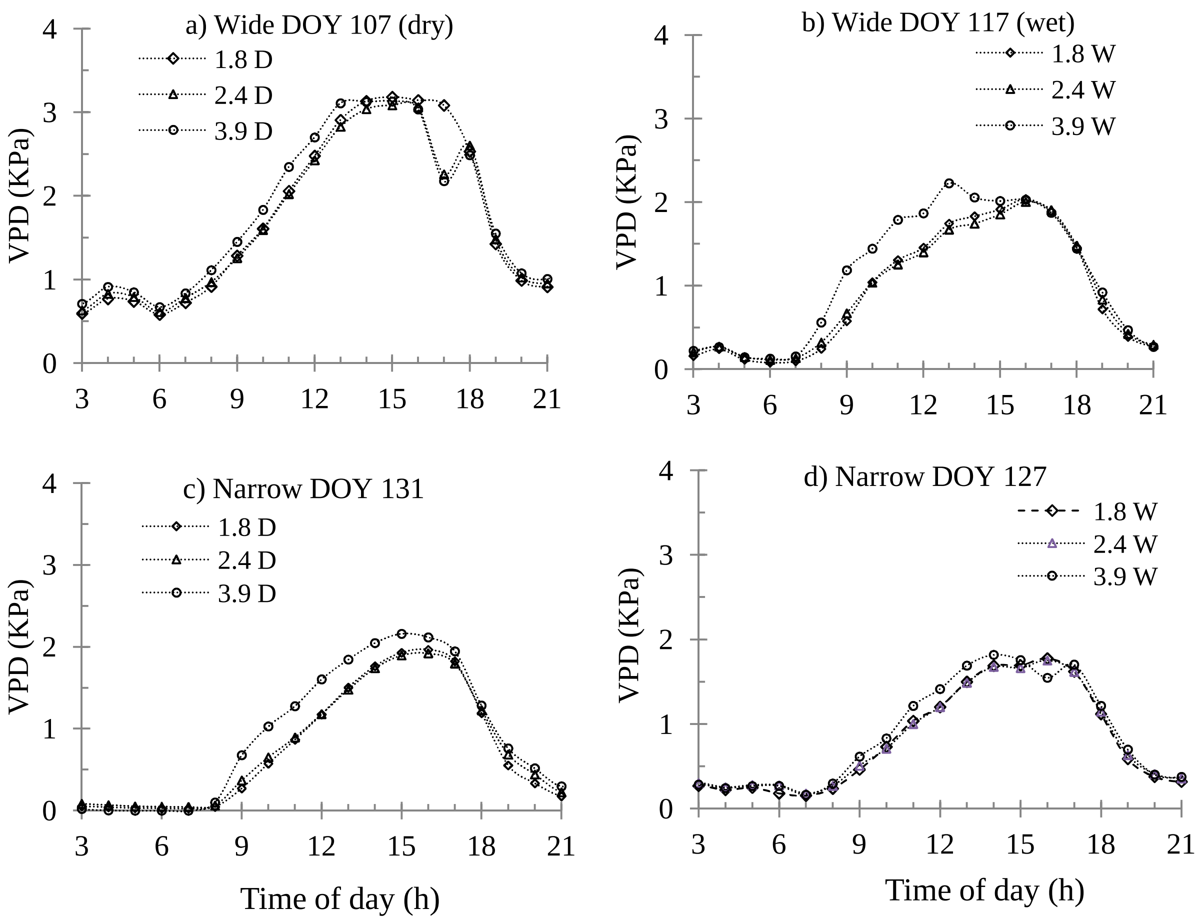


Figure 9.11 Atmospheric water vapour pressure deficit (VPD) pattern of diurnal variations for different layers during a) dry day on wide (DOY 107), b) wet day on wide (DOY 117), c) dry day on narrow (DOY 131) and d) wet day on narrow (DOY 127. The wet and dry periods represent by W and D.

On the narrow treatments, on a dry day the reference level VPD was 0.5 KPa higher than that measured within the canopy and they were more similar on a wet day, after receiving a relatively larger amount of rainfall (DOY 127) (Table 9.1 see Section 9.2.2) (Fig. 9.11c&d). The value of VPD at midday on the wet days (DOY 117 & 127) was lower compared to a dry day (DOY 107 & 131). Thus the increment of the VPD with progressing diurnal radiative energy was slow and attained its maximum in the late afternoon at 15:00 hours. The maximum VPD over the narrow strips was observed at reference level during the dry day, at about 2.2 KPa at 15:00 hours, whereas on the wet day VPD reached a maximum of 1.8 KPa (Fig. 9.11c&d). From the comparison of the wet and dry days, it can be seen that the VPD on the wet day maintained a more constant value between 14:00 and 16:00 once it nearly reached its maximum of about 1.75 – 1.90

KPa (Fig.9.11c&d). The possible reason is due to the cooling effect on the air within the crop canopies and less mixing due to the closer rows.

Overall, as the air temperature changes, VPD can provide a better indication of the current atmospheric evaporative demand (de Jager & van Zyl, 1989), since it combines the effect of both temperature and humidity in a single value. However, wind also affects the VPD value in the crop canopy as it removes the moist air and usually replaces it with drier air under these semi-arid conditions (Allen *et al.,* 1998), but it depends on the moisture content of the incoming air and how much the air in the canopy is changing. In addition to water availability and uptake processes, the transpiration losses play a great role in rate of water movements in plants (Tanner and Sinclair, 1983). VPD is a main driving force for transpiration losses from leaves, especially in the upper part of crop canopies as it responds to the immediate surrounding environmental factors - temperature, water vapour, solar radiation and wind speed (Ray *et al.,* 2002). Among these environmental factors the wind speed has the most complex relationship with the VPD values, especially in the arrangement of row crops as there are advective effects from the adjacent dry land surfaces. In this study of IRWH, the size of the adjacent runoff strips may have an effect of generating advection between the maize plants sown in rows or on the side of the basin area. In order to evaluate this situation, two windy days have been selected for comparing the effect of wind on the VPD for the wide and narrow runoffs. The VPD data from late morning until the afternoon hours (10:00 - 16:00) have been used to determine the effect of wind speed on VPD and temperature on wide and narrow strips (Fig. 9.12 &9.13).

On the wide runoff strips on a windy dry day (DOY 112), the VPD values at all levels in the profile decreased (from 1.5 to 0.5 KPa) with increasing wind speed from 2.2 to 3.5 m s^{-1} within canopy, from 3.0 to 4.5 m s^{-1} just above canopy and from 4.3 to 6.1 m s^{-1} at reference level (Fig. 9.12). In a similar manner, the air temperature also decreased with increasing wind speed. Both the VPD and temperatures within and above canopy of the wide runoff strips had negative correlations with wind speed during the dry windy day (Fig. 9.12).

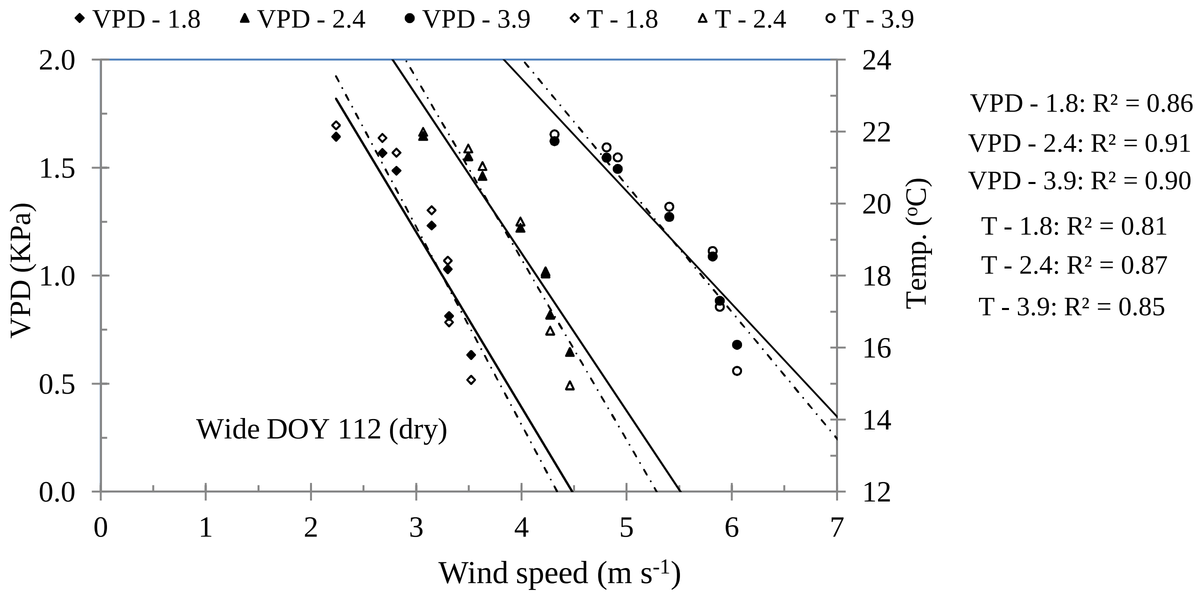


Figure 9.12 Change in vapour pressure deficit (VPD) and temperature (Temp.) with wind speed for a selected windy day (DOY 112) during the daytime from 10:00 – 16:00 on a wide runoff strip. Linear line denoted: solid line = VPD and dot-dash = Temperature.

On a dry day, when the surface is not wet, the latent heat energy is smaller than the sensible heat and an increase in wind speed is expected, which increases the sensible heat at the expense of latent heat (Fig. 9.12) (see Ch. 10). The strong wind on a dry day played a significant role to enhance turbulence, thereby reducing the boundary layer resistance above the canopy and, consequently, facilitating the movement of water vapour from the upper part of the canopy. In addition, strong winds also served as means of transporting sensible heat from the relatively dry runoff strip into crop rows. From Fig. 9.12 therefore, it is illustrated that, with an increase in wind speed VPD would increase for all profiles but with different wind magnitudes, due to the atmospheric and surface resistance. However, these VPD values were still small compared to days with higher temperature and lower relative humidity (for example, DOY 107). Monteith (1973) and van Bavel and Hillel (1976) described the effect of plant or crop resistance to diffuse water vapour movement or relative humidity of air on water flux losses from a dry surface.

On the narrow runoff strips, for the case of a wet windy day, VPD and temperature values have less dependence on the prevailing wind speed (Fig. 9.13). As the wind speed increases, the VDP over the wet plant surfaces increases and temperature profiles also tends to increase. The relations showed a fairly positive correlation with some scattered values.

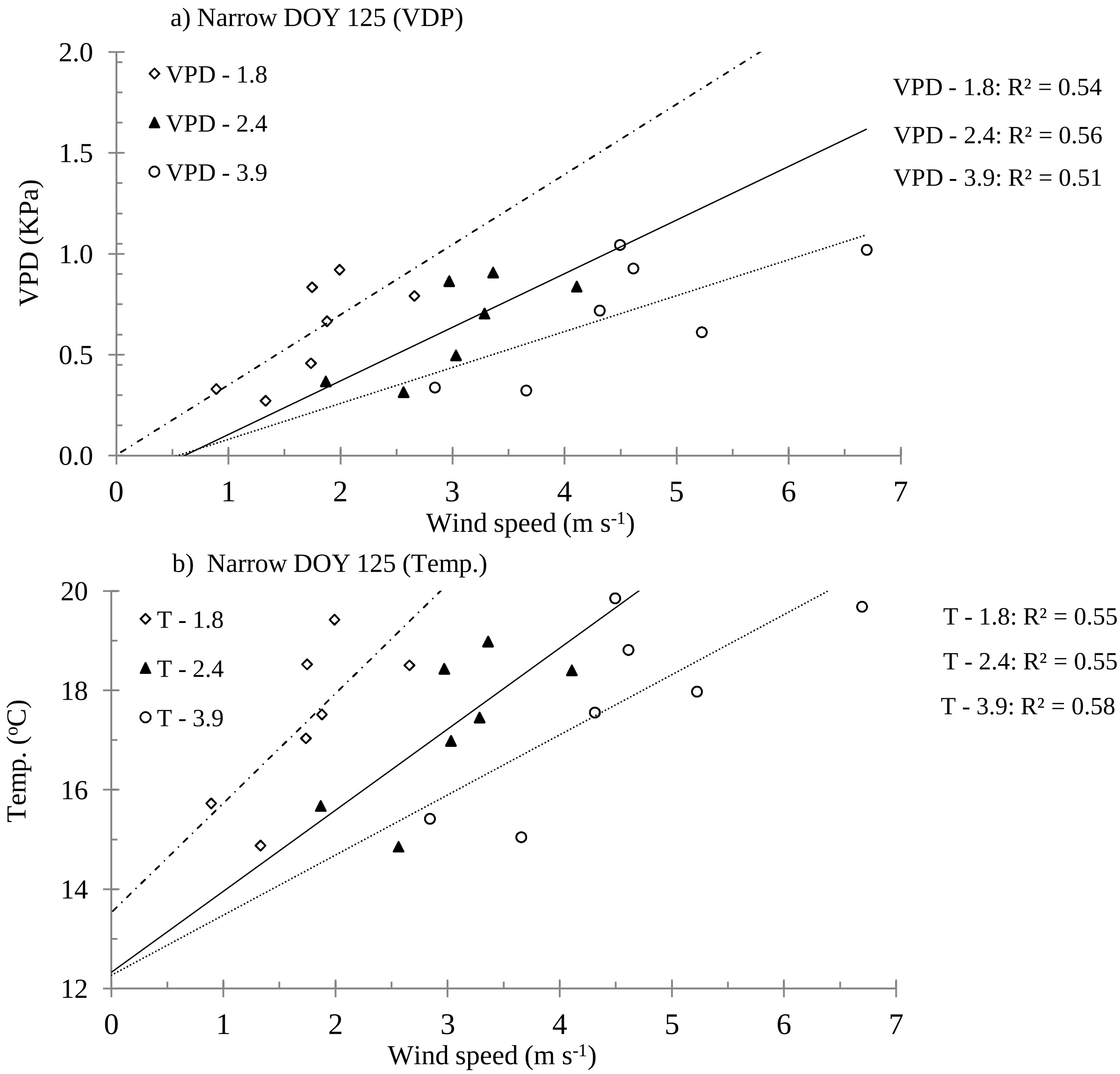


Figure 9.13 Change in vapour pressure deficit (VPD) and temperature (Temp.) with wind speed for a selected windy day (DOY 125) in a daytime from 10:00 – 16:00 on a narrow runoff strips at a range of levels above the soil surface. Linear line denoted: dot-dash = 1.8 m, solid line = 2.4 m and dotted = 3.9 m.

Note that, VPD over the wet surfaces always increased with increasing wind speed, but it depends on the availability of energy for latent heat of vaporisation and must remain in balance with sensible heat losses. The higher VPD gaves a greater driving force for evaporation loss from the canopy. The behaviour of increasing VPD with wind speed under wet day conditions means that more energy was used by evaporating water as transpiration while bringing more dry air to the crop canopies. Therefore, in the case of narrow runoff strip, during the wet days (Fig. 9.13), the advection of the sensible heat by the wind into the crop rows caused a stronger VPD or water vapour gradient. These situations of local advection often occur, when a high wind speed was present in the runoff section. However, as long as the upwind fetch was assumed to be fully or partially sufficient, only the locally generated advective effect would be measured in the row crops. The origin of the sensible heat for the local advection depends on the state of the soil surface, particularly whether wet or dry, as well as on the width of the runoff strip which is generating the advection (see Chapter 10, Section 10.4.3).

It is expected that wide runoff strips for both wet and dry conditions will have higher advection compared to narrow runoff strips. Kanemasu and Arkin (1974) reported the importance of within row advection for sorghum plants sown on wide and narrow strips of 0.91 m 0.46 m row spacing. They found that, evapotranspiration from wide rows was about 10% greater than narrow ones, and was attributed to a higher transpiration rate in the wider rows due to the consumption of sensible heat generated at the soil surface. This is in good agreement with the study of estimation ET for wide and narrow using energy balance method (see Chapter 10), where the wide runoff strip had higher ET and used more energy to evaporate water compared to narrow runoff. For instance, the result from Chapter 10 showed ET around midday (11:00 - 15:00) on wide strips was higher by about 47% and 16% compared to narrow strips under IRWH system for dry and wet conditions. Hanks *et al.* (1971) referred to within-row advection of sensible heat generated on dry soil surfaces that can be also consumed by increased transpiration of the plants adjacent to the dry soils.

9.4 Conclusion

The IRWH tillage system studies included a wide (3 m) and a narrow (1.5 m) bare runoff strip with same size bare basin area of 1 m. The effects of these features on the surface boundary layer within and above canopy were investigated on a number of selected days after the crop reached maximum height. In both wide and narrow treatments, the wind speed of the profile increased with height. However, under the local advection conditions, there was the formation of a bulge (distortion) in the equilibrium height (just above the canopy) and in the thermal boundary layer at about 1.5hc height on narrow strips, a slightly deviation also occurred on wide runoff strips. Therefore, it was suggested that, the presence of the local advection in the wide runoff strips of a IRWH system could be a common phenomenon causing variations in water vapour removal under the heterogeneous nature of IRWH tillage system. However, it depends on the size of the runoff, degree of wetness of the soil surface and is more likely with higher temperatures and under windy conditions. In general, advection is more pronounced in wide runoff strips than narrow strips.

In addition, from the profile of θv and ea it is possible to derive an expression for thermal stability stratification which was shown to be influenced by the canopy structures (wide or narrow RSL) under wet and dry conditions. On wet days, the air layers just above the canopy grew rapidly which may continue throughout the day, whereas, on dry days, the growth of the mixing layer was very weak. However, in general on wide strips within the canopy the profile had a relatively more stable or near neutral condition than narrow strips. This tends to make the vertical turbulence in wide runoff greatly suppressed compared to narrow strips. It was also noted that, due to surface heating on the wide runoff strip, there could be unstable conditions shortly after sun rise which warmed the lowest layer above the canopy.

On the other hand, results showed that VPD and temperatures were strongly correlated with wind speed, which indicated the dependence of VPD on wind speed at all heights in the profiles between the rows of the IRWH system. From the present study, it was suggested that, profile characteristics within and above plant canopies are playing a great role in determining the VPD and consequently, can help to explain the transpiration rate of the crop. Furthermore, the study of the profiles of climate variables and VPD relations enhance the understanding of the heat energy exchange processes under this heterogeneous maize crop canopy of the IRWH technique.

CHAPTER 10

Comparison of Energy Available for Evapotranspiration under In-Field Rainwater Harvesting with Wide and Narrow Runoff Strips

10.1 Introduction

The Bowen ratio energy balance (BREB) method provides a practical approach with high precision to obtain reliable evapotranspiration (ET) estimates at field and crop scale (Gavilan and Berengena, 2007). Biomass production is related to the amount of transpiration and by promoting more efficient water use higher production levels may be obtained. In order to achieve higher water use productivity under conservation tillage practices, such as in-field rainwater harvesting (IRWH), the proportion of evaporation lost from the soil surface needs to decrease and transpiration needs to increase. Hence, a deeper understanding of the energy supply required for ET is needed and can be acquired by precise measurement of the energy and water budgets of a crop land.

Several micrometeorological and other methods have been used to determine ET at crop level, including the BREB method, eddy covariance, weighing lysimeter and sap flow gauges as well as adaptations to the Penman-Monteith model (Savage *et al.,* 1997; Jara *et al.,* 1998; Steduto and Hsiao 1998a and b; Savage, 2009). Recent studies have also shown that the energy balance of a cropped land can be obtained by various methods and models. Steduto and Hsiao (1998a) used the BREB method with gradient techniques to determine the diurnal pattern of fluxes of well-watered maize fields compared to adjacent maize fields using water stored in the soil. Zeggaf *et al*. (2008) applied the BREB method and partitioned ET of a maize crop into transpiration for the crop canopy and soil water evaporation at soil surface level; Chavez *et al.* (2009) developed an operational method to estimate hourly crop ET (sorghum and maize) using a two-source energy balance model, which showed good agreement with eddy co-variance and BREB methods. Zhao *et al.* (2010) simulated latent heat flux by using the Penman-Monteith (P-M) model and demonstrated that the application is reasonable for a relatively homogeneous maize field. Hipps and Kustas (2001) cautioned the use of the Penman-Monteith model over heterogeneous (sparse, non-uniform) canopy and surface conditions, because differences in canopy and soil surfaces had a significant influence on the energy balance. The comparison of different methods under a wide range of conditions, however, gives a variety of results with varying levels of soil water availability and amount of intercepted solar energy.

The aerodynamic method, corrected for stability of the atmosphere, is a recognized commonly accepted method to measure turbulent fluxes of sensible and latent heat over a cultivated crop field in semi-arid areas as shown by Oke and Schild (1970), Malek (1993) and Savage *et al.* (1997). This method relies on the existence of strong relationships between fluxes of sensible and latent heat via temperature, humidity and wind gradients. Stability correction factors have been proposed that modifies the original aerodynamic equation (Oke and Schild, 1970; Malek, 1993). Such modifications with different stability correction factors based on estimates of zero plain displacement height (d) and the roughness parameter (z_o) can result in sufficiently accurate measurements of sensible and latent heat fluxes (Oke, 1978; Monteith and Unsworth, 1990).

Water harvesting interventions are not widely evaluated in terms energy balance components, despite the broad base in quantifying water losses through ET in in-field rainwater harvesting (IRWH). Quantification of water loss by ET is of primary importance for monitoring and managing limited water resources at various spatial scales of field crops in arid and semi-arid areas (Lecina *et al.*, 2003; van Rensburg, 2010). A better understanding of energy balance exchange processes is necessary to quantify and explain the ET losses from IRWH under maize production with different runoff strip lengths. As the tramline, plant rows in the IRWH are arranged between bare runoff strips, it was therefore, hypothesised that they will give varying energy partitioning according to different runoff strip lengths. The purpose of the study was:

- to quantify the components of the energy balance; and
- to compare the available energy so as to estimate ET for a maize crop under IRWH with wide and narrow runoff strip lengths.

10.2 Theoretical bases

The micrometeorological method is based on the measurement of available energy (Rn - G) and direct or indirect measurements of sensible (Hs) and latent (LE) heat flux using the shortened energy balance equation (Rosenberg *et al.*, 1983):

$$Rn - G = Hs + LE \quad \textbf{10.1}$$

where all the terms, net radiation (Rn), soil heat flux (G), sensible heat flux (Hs) and latent heat flux (LE) are expressed in Wm^{-2} and the fluxes are considered positive when coming into the canopy or soil surface and negative for outgoing fluxes.

The BREB method combines the aerodynamic and energy balance methods to determine how the available energy is partitioned. The Bowen ratio β is the ratio of sensible heat flux (Hs) to latent heat flux (LE) and can be determined from gradient measurements in the atmosphere above a crop canopy (Rosenberg *et al.*, 1983; Rana and Katerji, 1996; Savage *et al.*, 1997):

$$\beta = \frac{Hs}{LE} \quad \textbf{10.2}$$

To derive Eq. 2, it is assumed that the coefficients of heat (*Kh)* and water vapour (*Kw*) are similar. Using energy balance Eq. 10.1 and Bowen ratio, LE can be determined as follows:

$$LE = (Rn - G)/(1 + \beta) \quad \textbf{10.3}$$

Heat, water and momentum exchange at a surface are turbulent processes often estimated from vertical gradients of temperature, water vapour and wind speed above the surface using flux gradient relationships. According to Oke (1987) and Monteith and Unsworth (1990) the modified aerodynamic equations for determining or calculating *Hs* flux can be written as follows:

$$Hs = \rho C_p k^2 \frac{(\theta_1 - \theta_2)(u_2 - u_1)}{\{ln[(z_2 - d)/(z_1 - d)]\}^2} (\Phi_m \Phi_h)^{-1} \quad \textbf{10.4}$$

where ρ_a is air density (1.4 kg m^{-3}); C_p is specific heat of air at a specific atmospheric pressure, *P* (J kg^{-1} K^{-1}); k = 0.41 is the von Karman constant; z is measurement height (m); d is displacement height (m); u_2 and u_1 are wind speed at two levels (m s^{-1}); θ_1 and θ_2 are potential temperature at two levels (K), and Φ_m and Φ_h are stability functions for momentum and heat, respectively.

The Richardson Number Ri is an important parameter that measures atmospheric stability. Ri is a dimensionless measure of the intensity of turbulence or mixing and provides a single criterion for existence or non-existence of a stable stratified environment (Arya, 2001). Using the logarithmic finite-difference approximation for wind speed and potential temperature gradients, the bulk Ri is expressed as:

$$Ri = \frac{g}{T} \frac{\Delta\theta}{(\Delta u)^2} ln \frac{z_2}{z_1} \quad \textbf{10.5}$$

where g = 9.81 m s^{-2} is gravitational acceleration; T is the average air temperature (K) over the height interval (m) of $(z_2 - z_{1)})$; $\Delta\theta$ is the change in potential temperature (K); and Δu is the change in wind speed (m s^{-1}).

According to Malek (1993) and Arya (2001), Ri is negative under unstable conditions, zero for neutral, and positive under inversion or stable conditions. Therefore the corresponding value of Monin-Obukhov (M-O) similarity stability parameter ($\zeta_m = z_m/L$) can be estimated as:

Neutral and stable: $\zeta_m = R_i/1 - 5R_i$ for $0 \leq R_i < 0.25$ **10.6**

Unstable: $\zeta_m = R_i$ for $R_i < 0$ **10.7**

where z_m is height in the surface layer and L is Obukhov buoyancy length.

According to Oke (1987), Monteith and Unsworth (1990), Malek (1993) and Arya (2001) the generalized stability factor, F ($F = [\Phi_m(\Phi_h \text{ or } \Phi_w)]^{-1}$) can be computed for stable conditions ($Ri > 1$) as:

$$\Phi_m^2 = \Phi_h = \Phi_w = (1 - 5\zeta)^{-1}, \quad \text{for } \zeta \geq 0, \text{ and } F = (1 - 5\zeta)^2 \quad \textbf{10.8}$$

and for unstable condition $(Ri < 0)$ as:

$$\Phi_m = \Phi_h = \Phi_w = (1 - 15\zeta)^{-1/2}, \quad \text{for } \zeta \geq 0, \text{ and } F = (1 - 15\zeta)^{-1} \quad \textbf{10.9}$$

where Φ_m , Φ_h and Φ_w are stability functions for momentum, heat and water vapour, respectively.

In addition, estimates of the roughness length parameter (z_o) and zero-plane displacement height (d) are needed in order to obtain accurate estimates of Hs and LE fluxes in studies that apply the aerodynamic method, as in this experiment (10.Eq. 4). According to Hanks and Ashcroft (1980) the soil heat flux at the surface (G_{sf})can be adjusted at a fixed depth of 0.08 m $(G_{0.08})$ for heat stored in the upper layer as follows:

$$G_{sf} = G_{0.08} + C_s \frac{dT_s}{dt} dz \quad \textbf{10.10}$$

where the specific heat of the soil (C_s) and the change in the soil temperature, dT_s (at depth of 0.02 and 0.06 m) over the output interval time dt are required to calculate the stored energy at dz the depth of soil heat flux plate (0.08 m).

To obtain the soil heat flux at the surface (G_{sf}) at a fixed depth of 0.08 m ($G_{0.08}$) for heat stored in the upper layer, the heat capacity of moist soil (C_s) was calculated by adding the specific heat of the dry soil to that of soil water ($C_s = \rho_a(C_d + \theta_m C_w)$); where ($C_s$) is the volumetric heat capacity ($Jm^{-3}K^{-1}$); ρ_b is average soil bulk density for the layer above the heat flux plate (kg m^{-3}, ρ_b = 1375 kg m^{-3}); θ_m is the mass basis soil water content (kg of water per kg of dry soil); Specific heat of most dry mineral soils (C_d) and soil water (C_w) are 840 and 4180 J kg^{-1} $^oC^{-1}$, respectively

The overall detailed evaluation of the empirical forms of similarity functions and their relationships have been described by Francey and Garratt (1981), Rosenberg *et al.* (1983), Monteith and Unsworth (1990), Savage *et al.* (1997) and Arya (2001).

10.3 Materials and methods

10.3.1 Experimental design

For this study, only two RSL treatments were selected, *viz.* 3 m and 1.5 m to represent a wide and a narrow runoff strip length, respectively. The micrometeorology observations were taken in the wide RSL treatment from day of year (DOY) 106-121 (first period) and in narrow RSL treatment from DOY 122-132 (second period), as sufficient instruments were not available for simultaneous measurements. Within this period, two days (one each with dry and wet conditions) were selected in order to describe and understand the diurnal changes within the RSL treatments. The criteria for selecting the days were based on the following prerequisites: days with clear sky and atmospheric stability conditions in terms of Ri. The atmospheric stability was calculated using the non-dimensional Richardson Number (Ri*)* parameter. The selected dry days were DOY 111 and DOY 122 for wide and narrow RSL treatments, respectively, and wet days were DOY 116 and DOY 129, respectively. DOY 116 followed a 7.4 mm rain event, while DOY 129 followed a 3-day rainy period (total rain 21.9 mm).

At this site during summer time, the predominant prevailing wind direction is north-west, therefore to meet adequate upwind fetch the South Eastern block was selected for the micrometeorological measurements. The resulting minimum fetch was approximately 150 m with a 2.2 m high maize crop in an adjacent field. Thus, the fetch requirement is partially fulfilled; if one assumes a fetch to height-above-surface ratio of 100:1 as a rule of thumb (Rosenberg *et al.*, 1983).

10.3.2 Background of ecotope

The climate of this ecotope is characterised by a high annual evaporative demand (2294 mm) and a relatively low and erratic rainfall (528 mm), resulting in an aridity index of a semi-arid climate (Middleton and Thomas, 1992). Kenilworth has mean annual minimum and maximum temperatures of 11.0^{o}C and 25.5^{o}C, respectively. The soil is classified as a Bainsvlei form, Amalia family (Soil Classification Working Group, 1991) or a Ustic Quartzipsamment (WRB, 1998). The A horizon is reddish brown with a fine sandy loam texture (particle size of 88% sand, 3.6% silt and 8.4% clay content). The soil is regarded as very suitable for dryland agricultural, because it is deep (2000 mm) and drains freely in the top and the upper sub-soil. The soil has excellent water storage capacity due to a soft plinthic horizon at 1500 mm, which stores excess drainage within the reach of crop roots, making it available during dry spells (Chimungu, 2009). Hereafter, the experimental site will be called the Kenilworth-Bainsvlei ecotope.

10.3.3 Crop parameters

The maize was planted in tramlines on either side of the basin in an E-W direction, 1.1 m apart at plant population of 18000 per hectare in all IRWH treatments. The plant spacing within the row was 0.44 m and 0.28 m in wide and narrow runoff strips, respectively, to obtain the target plant population across the whole area. The maximum maize height was 2.2 m. The basin leaf area ratio (BLAR), expressed as the leaf area measured divided by the basin area, gave values of 2.43 and 1.42 in the wide and narrow RSL treatments at full canopy cover, respectively.

10.3.4 Weather data and micrometeorological measurements

Automatic weather station: Instruments at Kenilworth consisted of a tipping bucket rain gauge (0.1 mm), cup anemometer and wind vane; a pyrometer and combined temperature and humidity sensor. Data from these instruments were used to calculate reference evaporation (ETo) using the FAO-56 Penman-Monteith method (Allen *et al.,* 1998).

In field measurements: Profiles of heat, mass and momentum were measured just above the canopy and at the reference level (4.5 m) of the RSL treatments. A tall mast, attached to a tripod stand was buried to hold the sensors arms firmly at different heights up to the reference level above the ground surface. The data-logger stored hourly values (means of 5-minute observation readings) of temperature, humidity and wind speed at heights of 2.4 and 4.5 m above ground surface.

The one-dimensional vertical wind profile was analysed in order to estimate z_o and *d* by iteratively applying *d* to a form of the logarithmic wind law (Rosenberg *et al.*, 1983). Wind speed was monitored at eight heights (1.8, 2.1, 2.4, 2.7, 3.0, 3.3, 3.9 and 4.5 m) within and above the maize canopy, then plotted on a linear scale versus ($z - d$) on a log scale at near-neutral conditions using the criteria $0.00 < Ri < 0.25$ (Arya, 2001). The intercept on the ($z - d$) axis gives an estimate of roughness parameter z_o (Monteith and Unsworth, 1990). For maize under IRWH the estimates of *d* and z_o were found to tend towards 0.61 and 0.13 of the canopy height (*hc)* ($d = 0.61hc$ and $z_o = 0.13hc$), respectively.

10.3.5 Instrumentation

Wind speed was measured using three-cup wheel Sentry anemometers (Model 03001) with stalling speed of about 0.15 m s^{-1}. Temperature and humidity were monitored using HMP50 temperature and relative humidity probes (Campbell Scientific, USA), which contained platinum resistance temperature detector (PRT) and Vaisala-INTERCAP sensors for temperature and relative humidity, respectively. The HMP50 sensors were housed inside white six plate radiation shields (41303-5A Model).

The recording of net radiation (Rn) regarded as positive for incoming the energy directed away from the soil, canopy and atmosphere. The four flux plates used for soil heat measurement were installed at 0.08 cm depth. Plate installation was accomplished by excavating a shallow trench, creating small slits in one side-wall just smaller than the plate dimension then inserting the plate into the silt and back filing the trench. Hourly soil temperature profile was measured at depth of 0.2 and 0.06 cm. Therefore, according to Hanks and Ashcroft (1980) the soil heat flux at the surface (G_{sf}) at a fixed depth of 0.08 m ($G_{0.08}$) is adjusted for storage in the upper layer.

10.3.6 Modelling of net radiation

Net radiation was computed as:

$$Rn = \left[(1-\alpha)Rs \times FC_{eff}\right] - \left[(1-V_{sky})\epsilon_s \sigma T^4/BLAR\right] \quad \textbf{10.11}$$

where *Rn* is net radiation, *Rs* is solar radiation, α is albedo, FC_{eff} is canopy fraction effectivity, $(1-V_{sky})$ view fraction factor of the canopy from the soil surface, ϵ_s is soil emmisivity, σ Stephan Boltzman constant, T^4 is temperature and BLAR is the basin leaf area ratio.

Existing models were combined with empirical equations from the literature to simulate *Rn* at different lengths of runoff strip under IRWH technique. Oguntunde and van de Giesen (2004) maintain that crop land surface albedo (α) is influenced by canopy albedo (α_c) and soil surface albedo (α_s) as follows:

$$\alpha = \alpha_c - (\alpha_c - \alpha_s)exp(0.75BLAR) \quad \textbf{10.12}$$

Soil albedo which includes the effect of zenith angle of the sun and soil wetness and is calculated as:

$$\alpha_s = \alpha_{sw} + \alpha_{s\theta} \quad \textbf{10.13}$$

where α_{sw} is the soil albedo according to wetness (dry soil: α_{sw} = 0.24 and wet soil: α_{sw} = 0.18). The soil albedo as a function of zenith angle (θ’) of the sun (Song, 1998) was calculated as follows:

$$\alpha_{s\theta} = 0.01[(exp0.00358\theta'^{1.5}) - 1] \quad \textbf{10.14}$$

$$\theta = \arccos(sin\emptyset sin\delta) + (cos\emptyset cos\delta)\left[\frac{\pi}{12} - (t - t_o)\right] \quad \textbf{10.15}$$

where α_s is soil albedo based on soil wetness, $\emptyset$ is the latitude of the location, δ is solar declination as a function of the day of year, t is time of day and t_o is time of the solar noon.

Long-wave radiation emitted from the surface also contributed to the radiation balance to the canopy. To consider the effect of outgoing long-wave radiant variations, the view fraction factor $(1-V_{sky})$ of the canopy from the soil surface were used according to Ham *et al.* (1991):

$$V_{sky} = \left[\{(L_R - L_c)^2 + h_c^2\}^{1/2} - h_c\right]/L_R \quad \textbf{10.16}$$

where L_R is the runoff strip length, L_c is the inter-row/canopy width , and h_c is canopy height.

The above equations (Eqs. 10.11-10.16) were used to compute *Rn* values at different sun angles both in wide and narrow treatments. Modelled *Rn* values were also compared with the observed values available only from the wide RSL treatment.

10.3.7 Statistical analysis

Analysis of variance was done on the results of the wide and narrow RSL treatments using the statistical software SAS for Windows (1999). Empirical relationships of (Rn – G) and LE were derived using regression procedures.

10.4 Results and discussion

10.4.1 Weather variables and atmospheric stability

The prevailing weather conditions during the two measuring periods, *viz*. DOY 106-121 (wide RSL treatment) and DOY 122-132 (narrow RSL treatment) were captured by the hourly changes in the solar radiation (Rs in Fig. 10.1a), air temperature (T in Fig. 10.1b), wind speed (u in Fig. 10.1c), relative humidity (RH in Fig. 10.1d) and rainfall (RF in Fig. 10.1e).

The measuring period of 25 days was during autumn, and as expected for that time of the year the solar radiation decreased slightly over the measuring period, resulting in a slightly higher mean daily air temperature over the first period (15.4^{o}C) compared to the second period (13.7^{o}C). The wind speed was generally weaker in the second period (1.9 m s^{-1}) compared to the first period (2.1 m s^{-1}), but there were days with peak wind speeds of 4.0 - 5.8 m s^{-1} during both measurement periods.

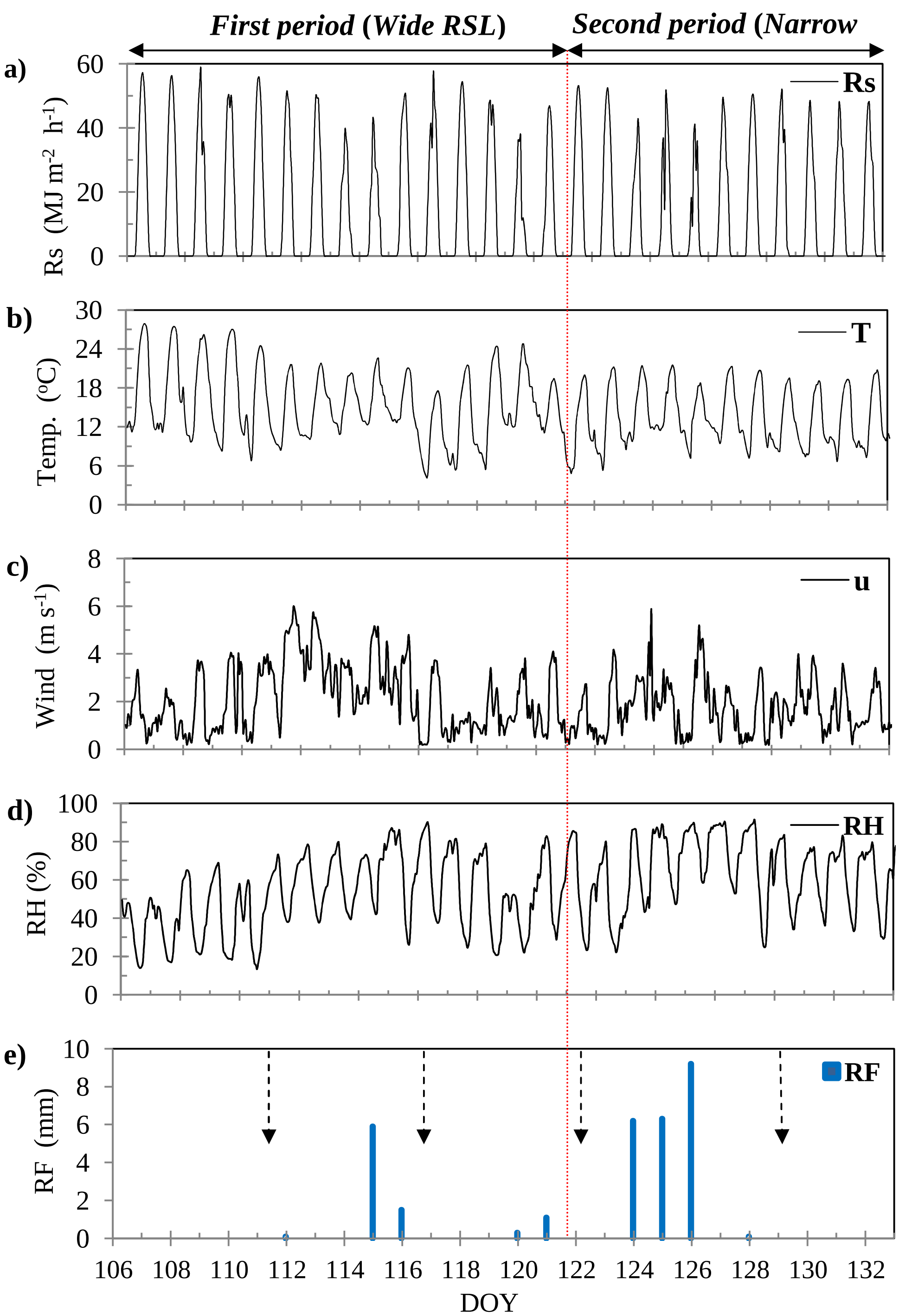


Figure 10.1 Hourly weather variables from automatic weather station measurement during the wide RSL treatment (16 April – 01 May) and narrow RSL treatment (02 May – 12 May): a) Solar radiation (Rs); b) air temperature (T); c) wind (u); d) relative humidity (RH); e) daily amount of rainfall (RF). The four arrows marked the days selected for the analysis.

In the absence of rain, the relative humidity was typical of semi-arid conditions with low values during the day and higher values during the night as temperature declined following the diurnal trend. The mean RH was slightly higher in the second period (63.7%) compared to the first period (52.7%), mainly due to more rain (21.9 mm versus 8.9 mm) and longer rain duration. These weather conditions resulted in a generally lower ETo in the second period compared to the first period.

Within and above the canopy, behaviour of wind and temperature is very complex, and is often characterized by the stability parameters. Thus the convective state for the flux measurement periods is determined by the stability parameter criterion. According to the atmospheric stability, the conditions in the first period generally had lower values of *Ri* than the second period. Despite these general differences in the weather conditions of the two periods, it was argued that there were days that met the requirements of the atmospheric stability criteria for comparing the RSL treatments. The selected days under dry and wet conditions, had relatively clear and calm night-time conditions showing stable atmospheric conditions, as seen by the *Ri* variation for each treatment on each day, for dry and wet periods (Fig. 10.2a and b) respectively.

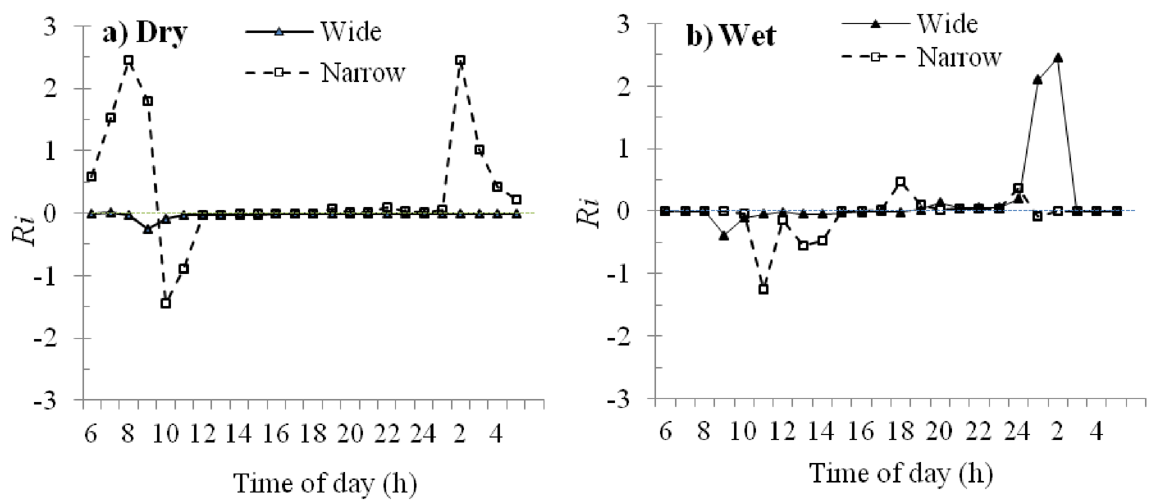
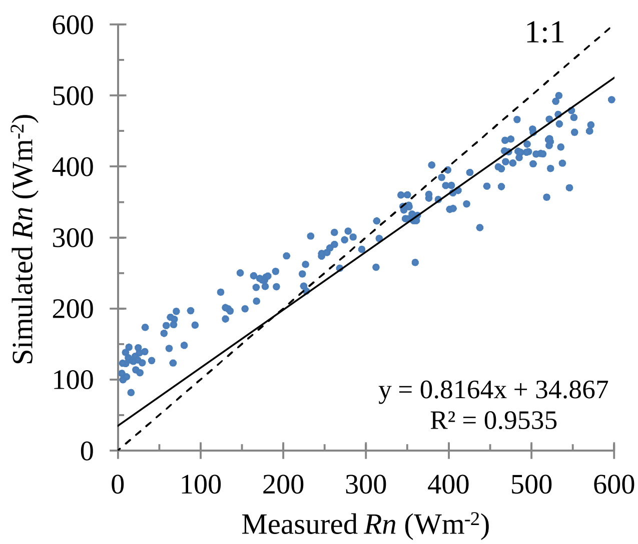


Figure 10.2 Diurnal variation in Richardson Number (*Ri*) on dry days (DOY 111 and 122) and wet days (DOY 116 and 129) for wide and narrow strip length treatments.

During wet days the narrow strip showed slightly negative *Ri* around midday, which indicates the dominance of mechanical turbulence. However, in general Ri for all selected days met the criterion for the existence of turbulence in stable and unstable stratified conditions, so the flux of heat and water vapour can estimated with inclusion of Ri stability parameter.

10.4.2 Estimation of net radiation

The diurnal net radiation is the fundamental driving force and is the variable used to estimate evapotranspiration. However, simultaneous measurement of Rn for both wide and narrow RSL treatments was not possible during this experiment, and so a simple model was used as an effective alternative. The Rn was only measured over bare soil in the wide runoff strip but simulated values of Rn include the effect of soil albedo and canopy structure factors. Thus, net radiation was estimated using Eq. 10.11 for 3 m and 1.5 m RSL treatments. The simulated Rn was found to be significantly higher in the wide compared to narrow RSL. On average simulated Rn was lower by 24% - 38% and 14% - 25% of the Rs values for wide and narrow RSL, respectively. The wide and narrow RSL day time average simulated Rn ranged from 115.0 - 421.9 Wm^{-2} and from 75.4 - 293.1 Wm^{-2}, respectively. The nocturnal Rn energy loss from narrow RSL was slightly greater than from wide RSL. The accuracy of the model was evaluated against the measured *Rn* using a linear regression and Willmott (1982) D-index value (Fig. 10.3).



n	360
RMSE	62.36
RMSEs	47.01
RMSEu	40.97
MAE	50.52
R^2	0.95
D-index	0.98
RMSEs/RMSE	0.75
RMSEu/RMSE	0.66

Figure 10.3 Measured and simulated net radiation for the first measurement periods (DOY 107-121) data set.

The model was able to estimate *Rn* with a satisfactory degree of accuracy (D=0.98) and reasonable R^2 value (0.95). However, the RMSE was large (62.3 Wm^{-2}) for this measurement period. The systematic (RMSEs) and unsystematic (RMSEu) accounted for relatively large proportion of the RMSE with values 0.75 and 0.66 respectively. This implied that errors estimating Rn were associated with high variability of measured Rn values, due to the diurnal cycle as it varied each day from low values at sunrise and sunset to high values at midday. This meant that the measurement of Rn underestimated at lower (< 225 Wm^{-2}) and overestimated at higher (> 360 Wm^{-2}) solar radiant energy, but showed good relationships between 225 - 360 Wm^{-2}. This variation according to the amount measured Rn and the simulated one indicate that the complex nature of row crops and partitioning into soil and canopy components. Thus special attention is required in measuring Rn for the row crops arrangement, especially in IRWH techniques.

10.4.3 Comparison of diurnal pattern of energy fluxes

10.4.3.1 Dry days

During the two selected dry days (DOY 111 for wide RSL and DOY 122 for the narrow RSL) the *Rs* on both the wide and narrow RSL treatments had similar trends with only the thin cloud condition at 15:00 on the wide RSL treatment day (Fig. 10.4a) lowering the value by 93.5 Wm^{-2} (20%). During the middle of the day and in the afternoon, *Rn* showed little variation between wide and narrow RSL treatments (Fig. 10.4b) and the calculated Rn is used as input for the energy balance and partitioned into G, Hs and LE.

Measured soil heat flux (G) (Fig. 10.4c) was small compared to *Rn* being only between 3-17% of the midday *Rn* values a daily basis confirming previous researchers findings. For the wide RSL treatment, *G* exhibited a smooth trend with highest absolute value (52 Wm^{-2}) at midday, but the narrow RSL treatment was variable during the daytime with a larger absolute value peak at midday (76 Wm^{-2}) and during the afternoon (74 Wm^{-2}). In general, on a dry day the absolute values of G were less in the wide RSL compared to the narrow RSL in the daytime and about equal during night time. So during a dry day the narrow RSL treatment which effectively has a lower plant population over the basin area (and lower BLAR of 1.42), allowed more radiant energy to reach the soil surface and be conducted into the soil profile compared to the wide RSL treatment with a higher BLAR (2.43). This meant that, in the narrow RSL treatment more heat energy was transmitted or conducted at the soil surface than the wide RSL and therefore there was less energy available for partitioning into Hs and LE.

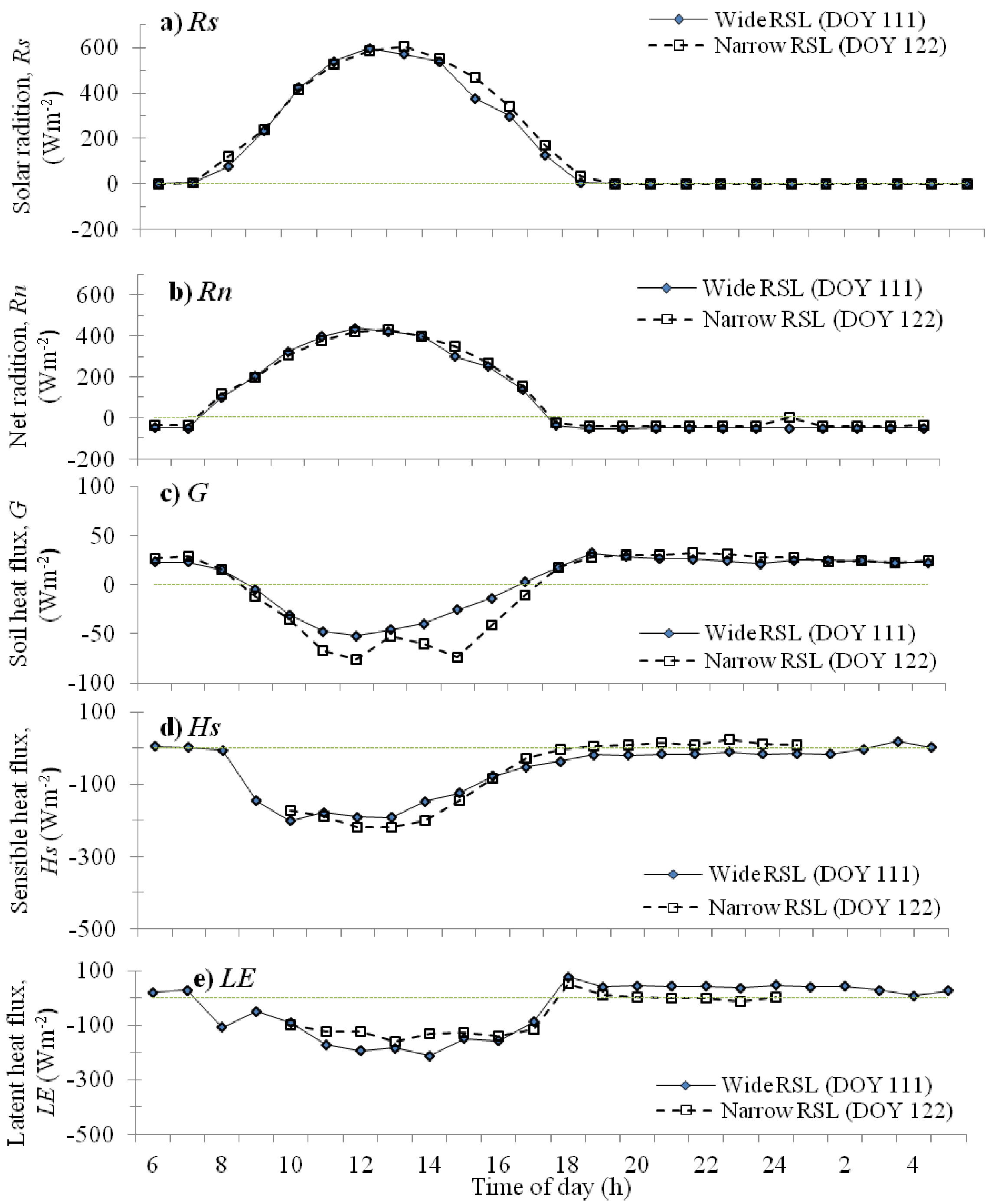


Figure 10.4 Heat fluxes during a dry day induced by the wide (21 April; DOY 111) and narrow (on 02 May 2009; DOY 122) RSL treatments: a) solar radiation (Rs); b) net radiation (Rn); c) measured soil heat flux (G); d) sensible heat flux (Hs); e) latent heat flux (LE).

The *Hs* (Fig. 10.4d) followed the same diurnal trends for both wide and narrow RSL treatments, but the absolute values of Hs for narrow RSL were greater than wide RSL between 11:00 and

15:00. During night time, Hs in narrow RSL was towards the soil surface, illustrating the direct exchange of heat from the canopy to the soil, which tends to influence the magnitude of LE, despite it being minimal during the night. The sharp increase of the absolute value of Hs in wide RSL during morning hours indicated that the wide open surface of the runoff area was releasing heat to the atmosphere. However, after midday through the afternoon more heat left the narrow RSL than the wide RSL.

On the wide RSL treatment, the LE ranged between 170 – 212 Wm^{-2} around midday (11:00-14:00), in contrast to Hs remaining almost constant at about 180 Wm^{-2} through the 11:00 to 14:00 period after reaching the highest value in late morning (Fig. 3e). In this case, around midday, more than half (55%) of the available energy was used for evaporating water from the wide strip treatment and β remained higher ($\beta = \sim 1$) around midday compared to morning and late afternoon, confirming that Hs is less than LE despite being almost similar values during the morning.

On the narrow RSL, the H*s* and LE followed a similar trend to the wide RSL (Fig. 10.4d and e). The energy was partitioned almost equally between Hs and LE. This was due to the radiant energy absorbed by the canopy and soil surface being conducted into the soil. The consistent negative *Hs* values indicated that the flux was away from the soil towards the canopy throughout the day, with maximum value near 220 Wm^{-2} occurring at 13:00. This shows that fluxes of *Hs* within the narrow RSL together with a canopy directly heated by radiation, resulted in higher canopy temperature and thus higher transpiration. However, observations during dry conditions show that wide and narrow RSL treatments had different Hs and LE partitioning. On DOY 111 (wide RSL) with a BLAR of 2.43 most energy was partitioned to *LE*, ($\beta \leq 1$) which could have included advection after 14:00, shown by high wind speeds (4.8 - 6.0 m s^{-1}) from the late afternoon until the evening. While, on DOY 122 (narrow RSL) with a BLAR of 1.42, a large portion of energy was partitioned to Hs ($\beta \gg 1$) around midday, and conditions were non-advective except for a short time in the late afternoon at 16:00 - 17:00.

10.4.3.2 Wet days

Following the period of rainy conditions, but under a clear sky (DOY116) except with a dip due to cloud at midday, Rs and Rn had larger values for the wide than the narrow RSL treatment in the afternoon (Fig 10.5a and b). From 13:00 to the afternoon, the wide RSL *Rs* slowly declined from a peak of 665 to 507 Wm^{-2} and *Rn* declined from 535 to 422 Wm^{-2}. The maximum *Rn* value only reached 450 Wm^{-2} at noon for the narrow RSL measurements after rainy days. There was also an effect of clouds with a *Rn* decline in the afternoon reaching a small plateau or slight rise in the late afternoon (16:00). This could have been due to less radiant energy penetration through the canopy, due to high LAI, as radiation was intercepted in the upper portion of the canopy with the mutual shading of the narrow strip plants.

In the morning, G for the wide and narrow runoff followed similar trends, with G for wide slightly more than that of narrow (Fig. 10.5c), but under cloudy conditions at midday and in late afternoon it was reversed, with less heat leaving the surface of wide RSL compared to narrow RSL. At night G values were positive, with wide RSL G of about 32 Wm^{-2} which was greater than narrow RSL by 25%, indicating more heat energy was going towards the wide runoff surface.

In contrast to dry days, during wet conditions the fluxes *(*Hs and LE*)* were not similar through the daytime (Fig. 10.5d and e). In wide RSL, the highest LE value had an absolute value of 374 Wm^{-2} at 13:00. The Bowen ratio partitioning (Hs/LE) was mostly positive during daytime hours but did not rise above 0.45. This meant that wetting of the surface soil in the wide runoff strip dramatically altered the surface energy balance as well as the microclimate in the canopy because of the reduced albedo and increased absorption of radiant energy (Table 10.11). This is when Hs comprise a relatively small portion of the energy balance (i.e. $\beta < 0.5$) under moderately windy conditions (2.8 m s^{-1}). In this case, in the wide RSL LE accounted for most of the energy consumption in the typical daytime, while LE was reduced in the late afternoon. On DOY 129 (narrow RSL), the prevailing temperature and wind speed were lower particularly after midday and there was little evidence of sensible heat advection.

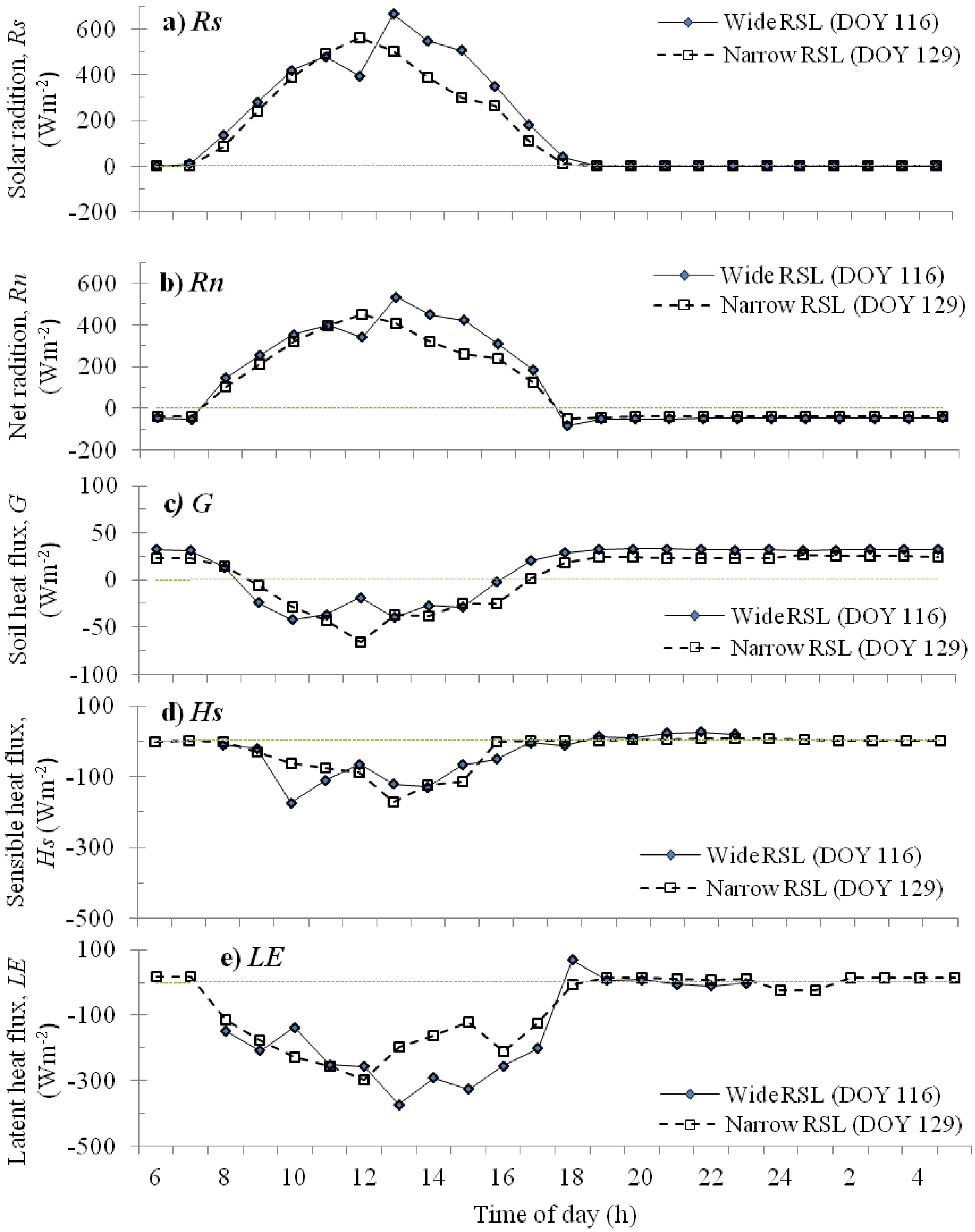


Figure 10.5 Heat fluxes during a wet day induced by the wide (26 April; DOY 116) and narrow (09 May 2009; DOY 129) RSL treatments: a) solar radiation (*Rs*); b) net radiation (Rn); c) soil heat flux (G); d) sensible heat flux (Hs); e) latent heat flux (LE).

From the analysis, the diurnal course of LE showed different values during dry and wet conditions. After the rain, G decreased more than on dry days, particularly after midday. G in both dry and wet periods for both wide and narrow RSL treatments represents a significant form of the energy transfer. The Rn after rain days was more variable than on dry days, probably due to diurnal change in soil temperature affected by canopy shading and changing calculated soil albedo caused by changes in soil surface water content. Besides, one can consider local advection of heat and water vapour within the air space in the uneven row widths inherent in the system of IRWH. This implies that the runoff area is favourable for horizontal advection from hot, dry, bare runoff area to a relatively cool, wet plant canopy in the basin area under windy conditions.

10.4.3.3 Midday basis of available energy partitioning

As the daily *Rn* peaks occurred around midday, the average (11:00 – 15:00) of the energy flux partitioning for the selected days on both wide and narrow runoff treatments during dry and wet conditions will be used in the comparison (Table 10.1). The average fraction of the available energy (EF), calculated as the ratio of the latent heat flux over the available heat energy [LE/(Rn - G)], shows that wet conditions were more efficient than dry conditions and the wide RSL was more efficient than narrow RSL (Table 10.1).

Table 10.1 Analysis of variance comparison of mean of values around midday (11:00 -15:00) for energy balance components for wide RSL (DOY 111 and 116) and narrow RSL (DOY 122 and 129). Where Rs: solar radiation; Rn-G: net radiation – soil heat flux; Hs: sensible heat flux; LE: latent heat flux; EF: average fraction on available energy; β: Bowen ratio; ET: evapotranspiration; ETo: reference evaporation.

Soil condition	Runoff strip	*Rs* (Wm^{-2})	*Rn-G* (Wm^{-2})	*Hs* (Wm^{-2})	*LE* (Wm^{-2})	*EF* (LE/(Rn - G))	β (*Hs/LE*)	*ET* (mmd^{-1})	*ETo* (mmd^{-1})	Temp. (^oC)	Wind (ms^{-1})
Dry	Wide	523.6	349.0	166.9	182.1	0.52	0.92	1.57	3.06	19.92	4.9
	Narrow	548.9	328.5	137.3	133.8	0.41	1.01	0.82	2.50	15.86	3.6
Wet	Wide	519.3	398.5	98.6	299.8	0.75	0.33	2.74	3.02	19.48	2.8
	Narrow	450.4	325.7	114.7	206.7	0.63	0.63	2.28	2.18	17.45	2.7
	LSD	ns	ns	ns	ns	ns	ns	ns	ns	-	-
Soil condition											
Dry (mean)		536.3	338.8	152.2	157.9b	0.46b	0.97	1.20b	2.78	17.9	4.2
Wet (mean)		484.9	362.1	106.7	253.2a	0.69a	0.48	2.51a	2.60	18.5	2.7
	LSD	ns	ns	ns	47.1	0.07	ns	0.41	ns	-	-
Runoff strip											
Wide (mean)		521.4	373.7a	132.8	240.9a	0.64a	0.63	2.16a	3.04a	19.7	3.9
Narrow (mean)		499.6	327.1b	126.1	170.2b	0.52b	0.83	1.55b	2.34b	16.7	3.1
	LSD	ns	41.7	ns	40.7	0.08	ns	0.37	0.52	-	-
	CV%	13.8	12.2	38.8	23.5	13.9	58.7	24.2	12.8	-	-

means followed by the same letter are not significantly different (P< 0.05, LSD = least square deviation, CV = coefficient of variance and ns = no significant difference).

The data set on energy balance components were highly variable with CV ranging from 13% to 58% (Table 10.1). The analysis of variance indicated that both soil conditions (dry and wet days) and runoff strip length treatments showed significant differences (P < 0.05) for the hourly values measured around midday. However, the interaction effect of the treatment (soil condition × RSL) had no significant differences on the energy balance components (not shown). The results indicate that there was no significant difference in available energy (Rn-G) between dry and wet days, but the wide RSL showed higher significant values of *Rn – G* (373.7 Wm^{-2}) compared to narrow RSL. As a result the fraction of available energy gave greater values for wide (64%) compared to narrow RSL (52%). Similarly the available energy for evapotranspiration was significantly higher during wet days (69%) compared to dry days (49%).

During dry days, the wide RSL showed higher fluxes of Hs and LE than the narrow RSL, with differences of about 30-50 Wm^{-2}. From the Bowen ratio, Hs was the larger portion of the available energy ($\beta \geq \sim 1$) during dry days. The mean value of β around midday was doubled on dry compared to wet days. This illustrated the domination of Hs during dry conditions although the evaporative fraction gave significantly greater values for wide compared to narrow strips. This implied that higher ET occurred from the wide runoff (2.16 mm d^{-1}) relative to narrow RSL (1.55 mm d^{-1}), with a significantly higher available energy on a wide than narrow RSL.

Under dry conditions, the LE only used 41 or 52% of the available energy from the narrow and wide strips, respectively. Compared to wet conditions where 63 and 75% of the available energy was used for the narrow and wide strips, respectively. This was probably due to the high soil water content in the top soil that could be evaporated. Both the energy balance calculations and the FAO 56 method of calculating the evaporation showed that for both wide and narrow runoff strips, the evaporation was lower under the dry conditions than during wet conditions. This occurred despite the ETo being higher during the dry period (3.06 and 2.50 mm d^{-1}) compared to the wet period (3.02 and 2.18 mm d^{-1}) for wide and narrow RSL respectively. Regardless of whether the conditions were wet or dry, the LE of the wide RSL was always larger than for the narrow RSL. If one considers the available evaporative surfaces of both the soil surface and the leaf surfaces, then both are much larger under the wide RSL. This influences the amount of water that is then evaporated as shown by the calculated differences in ET.

10.4.3.4 Partitioning of available energy (Rn - G)

The absolute value of latent heat fluxes from both the wide and the narrow RSL treatments were clearly increased with an increase in the available energy under both dry and wet conditions (Fig. 10.6). The linear regressions between LE and (Rn - G) gave reasonable values for the narrow RSL treatment with R^2 of 0.88 during dry conditions and 0.93 during wet conditions. Similar values were found for the wide RSL treatments with R^2 of 0.87 during dry conditions and 0.96 during wet conditions. The paired values were also highly significantly different ($P < 0.0001$) for the wide and the narrow RSL treatments as well as for dry and wet conditions, showing the differences between the RSL treatments. Using the BREB method, a similar result was obtained by Ham *et al*. (1991), however Zeggaf *et al.* (2008) found no significant differences in computing *LE* from the available energy for an open sparse maize field (4 plants m^{-2}) with wet and dry soils.

During a dry day the narrow RSL showed higher LE values (64%) with increasing amount of available energy than the wide strips (59%), in particular when Rn - G was more than 200 Wm^{-2}. During a wet day the wide RSL LE used more available energy than the narrow strips, probably due to more readily available water from the wet soil surface. Therefore, in comparing the effect of runoff lengths on LE dependence on available energy was stronger for wide runoff during wet days using more than 70% of available energy. In contrast, on the narrow RSL treatment, the LE used more available energy on dry days. This indicated that as the soil in the narrow RSL dried, the surface resistance increased, soil water evaporation decreased significantly and water losses were mainly or solely by transpiration from crop canopies.

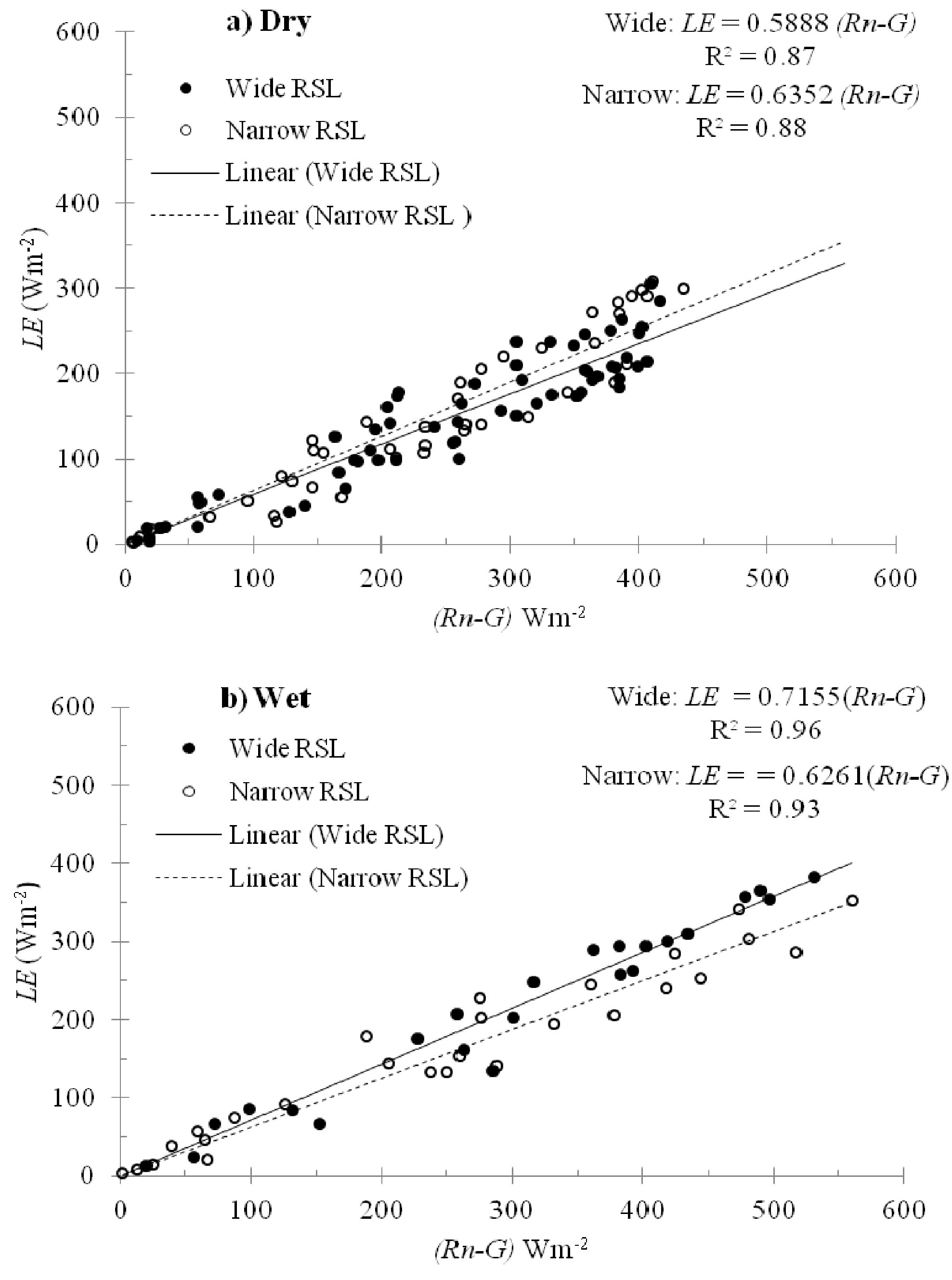


Figure 10.6 Relationship of available energy and latent heat flux measured at an hourly rate for wide and narrow RSL for calculated data from 8:00-17:00 (Solid-line = wide and dotted-line = narrow) in dry (a) and wet (b) conditions.

From the IRWH energy balance study it can be noticed that management practices play a great role, particularly those aimed at reducing soil water evaporation and increasing transpiration at the field level. Thus, the results from both wide and narrow RSL showed a dependence of ET on the amount of available energy during both wet and dry periods, but wet periods had much higher available energy partitioned to LE than the dry periods. These results agreed with the energy balance study of a maize field reported by Steduto and Hsiao (1998b) and Zeggaf *et al.* (2008). Similar results were also reported for other crops, such as cotton (Ham *et al.*, 1991) and vineyards (Yunusa *et al.*, 2004).

10.5 Conclusion

The method applied in this experiment of IRWH was used in order to quantify energy balance components and compare available energy as an estimate of ET for the wide and narrow runoff strips. Results primarily indicated that *Rn* simulation was satisfactory with the inclusion of albedo and canopy factors for the diurnal changes. Secondly, during dry and wet conditions G had variations in both wide and narrow RSL. Thus, the contribution of both Rn and G to the available energy had a great influence on partitioning of Hs and LE in the IRWH system.

The diurnal pattern of the Hs and LE was influenced by the prevailing weather conditions as well as canopy structures. Energy balance micrometeorological method can be used for description of the different farming conservation agricultural systems, but interpretation is limited by lack of simultaneous measurements, which means that assumptions had to be made. The two days chosen for the dry conditions were similar and comparisons made can be trusted. The two days chosen for the wet conditions were, however, more dissimilar and thus care must be taken with these comparisons. The differences included different amounts of rain received during different time periods, as well as the midday temperatures of the wide wet day was about 2.0^{o}C higher than that of the narrow wet day, and the wide had Rs 519.3 compared to the 450.4 Wm^{-2} on the narrow wet day which is 15% more available energy. Therefore it is important to compare the values of ratios or relative percentages to avoid misinterpretation of the data. Despite this reservation, the wide-wet was able to convert 75% of available energy into evaporative power. The discussion about the proportion of available energy that is converted to transpiration compared to soil evaporation is covered in another part of the study (Tesfuhuney, 2012).

Therefore it is concluded that by comparing the wide and narrow runoff lengths, with basin leaf area ratio of 2.43 and 1.42 respectively, the high BLAR contributed to greater transpiration on wider runoff strips and can cause loss of more energy by evaporation than on narrow runoff strips.

The local advection from the runoff area enhanced more evapotranspiration from the crop rows of the basin area. Thus, the LE flux is higher in wider runoff strips due to a higher fraction of available energy after rain days (wet days) when more soil water was available to crops through IRWH. Hence latent heat consumed more energy and as a result wide runoff was a more efficient converter of available energy to transpiration that also promotes more biomass production.

CHAPTER 11

General Conclusions

Sustainable food production in semi-arid areas depends mainly on the availability of water for the crops. The major problem of crop productivity in semi-arid area is the shortage of rainfall, together with its unfavourable distribution through the season. Therefore, improved strategies, such as in-field rainwater harvesting (IRWH) are of utmost importance to sustain dryland farming practices, and hence to maintain crop production. Consequently, promotion of improved surface treatments such as optimising runoff to basin area ratios and applying a mulch as a cover can contribute to improving the efficiency of rainwater productivity. As there is much competition for the dry stover from the livestock farmers, it is important to be able to show that it will make a large difference to the crop production. Therefore, evaluations of potential comprehensive cultural management strategies are crucial to improve the understanding of soil, crop and climate processes within the technique of IRWH.

The approach presented in this study encompassed and evaluated the soil water balance and energy balance components for better maize production under a system of IRWH for a semi-arid area under the Kenilworth Bainsvlei ecotope as an example of a fine sandy loam soil. As Kenilworth Bainsvlei ecotope has different features from the ecotopes where IRWH has been implemented before, with high clay contents and/or steeper slopes, these results tend to broader the application of IRWH. Another new investigation is that of the energy balance above and within the maize crop canopy in order to describe the fluxes of water and energy driving the system. Different surface treatments (runoff strip length, RSL and mulch cover level, ML) were evaluated to test the research questions *viz.* what are the optimal surface treatments? and how the microclimate of the maize cropped field changes with different runoff strips lengths. Therefore, this study hypothesised that these two aspects, water and energy supply and demand, need to be balanced or complement each other in the IRWH technique, in order to satisfy both soil water availability and energy availability in the system of IRWH. Based on this hypothesis and the field experiments and theoretical empirical calculations, several results have been presented in this study:

11.1 Soil water balance components and maize crop productivity under IRWH

Predicting runoff from rainfall characteristics: The in-field runoff results obtained from field measurements proved that by increasing the runoff strip length (to 3m) together with the addition of mulch cover caused the runoff to decrease, thus limiting the run-on water able to accumulate and infiltrate to the basin area. However, they simultaneously increased the infiltration on the runoff area under the mulch, so the water was still available to the crop. During the growing season, the highest runoff of 43% of the seasonal rainfall was observed on bare narrow runoff strip of 1 m and lowest runoff was from a wide 3 m RSL with full mulch cover. The fine sandy loam textured soil of the Bainsvlei Kenilworth ecotope, with deep and freely drained soil profile, could provide enough rainwater storage capacity to carry a maize crop through dry spells. So one needs to be able to balance the frequencies of the rainfall and the soils storage capacity with the amount of water the specific runoff strip length can potentially generate to supply the crop requirements. The results obtained from the simulated runoff confirm that the amount of runoff produced from a given length of runoff strip was a function of rain amount and intensity as well as surface treatments (RSL and ML) with a coefficient of determination (R^2) of 0.69. As a result, the long-term rainfall data analysis showed that at 80% probability the basins under bare narrow 1m length treatment have a rainwater advantage, while at 40% probability the wide 3m length runoff with full mulch cover has the rainwater advantage due to infiltration on the runoff area. Therefore, it can be concluded that the fine sandy loam soil of the Bainsvlei Kenilworth ecotope was suitable for use of the technique of IRWH, due to its high soil water storage capacity.

Partitioning of rainwater into basins and runoff strips: In the basin area or planting zone, the rainfall canopy interception (RCI) is a distinct process that needs to be included in the water balance for the IRWH technique. In this study the estimated rainfall interception by the canopy differed according to runoff lengths (due to plant density differences) and crop growth stages. The estimation of RCI revealed that the highest interception was in the range of 4.5% to 9.0% of precipitation for various RSL treatments. However for small rain events and during the initial growth stage, RCI was insignificant as either there was little water to be intercepted or the leaf area was too small. In general, the RCI capacity of a maize field under IRWH reached a plateau at about 0.5-0.6 mm for narrow RSL, and 1.0-1.1 mm for wide but it is important to note that the RCI efficiency was dependent on both the rainfall characteristics and surface treatments (particularly length of runoff strips). This implies that the RCI losses (water that would be evaporated from the canopy and not available for infiltration) from wide treatments, was higher than those from narrow RSL treatments, and it needs to be included in the water balance calculation.

From the mean results of runoff-rainfall (RR) ratio, the lowest efficiency was observed for the fully mulched wide RSL treatments i.e. only about 4% of rainfall, while the highest mean RR ratio was about 27% from bare, narrow RSL-1 treatments. The medium RR efficiencies (about 10 - 11%) were observed on mulched RSL-1.5 and RSL-2 treatments. This variation in RR ratio clearly indicates that the partitioning of rain into basins and runoff strips depended on the surface treatments. The advantages of IRWH is that it concentrates the runoff water into the basin so that it can be used directly by the plants, whereas water infiltrated into the root zone on runoff strips only becomes available for crop transpiration by the mature crop during longer dry spells. Therefore the narrow RSL that collected 27% additional rainfall had an advantage over the wide RSL which made little additional water available to the crop. The results also showed that the treatment with the highest fraction of rainwater infiltrated (FI) was RSL-2, which was also more productive than the other treatments.

Quantification and predicting soil water evaporation: From the microlysimetric field measurements, it was confirmed that different positions in the basin and across the runoff area rendered different amount of water evaporation from the soil surface (Es). This reduction in Es was affected by shading of the soil surface by the crop and mulch cover. This study of Es beneath a maize canopy gave good results when using soil physical parameters to predict Es using both Ritchie (α') and Stroosnijder (β') models. The values for α' in the range 2.34 – 4.26 and for β' 1.38 – 2.06, were in similar ranges to values found in the literature but were not easily related to different treatments in basin and 1 m runoff strips. However, these α' and β' values showed little variation according to the effect of canopy shading or mulch cover. The evaluation of Es models demonstrated that the simulated Es were underestimated by the Ritchie model which is dependent on time after wetting and overestimated by the Stroosnijder model where atmospheric evaporative demand is used. The RMSE and MAE were higher in β' model than for α' model; with RMSE values for different canopy shading and mulch cover in range of 5.92 –

1.02 mm for β' and 5.11 – 0.54 mm for α'; and MAE values of 5.44 – 0.92 mm for β' and 4.46 – 0.49 mm for α'. The detailed results indicated that the time α'-model performed well to estimate ∑Es from the basin area (FC-BA) and the potential evaporation β'-model performed better for unshaded runoff strips (UC-RA). However the consideration of weather parameters may have an advantage, since the microclimate of the cropping system changes according to surface treatments in the system of IRWH. The microlysimeters used in this experiment made it possible to measure daily and compute cumulative evaporation rate beneath maize canopies across the basin and runoff section of the IRWH structures and develop appropriate factors for Ritchie and Stroosnijder equations.

Estimation of soil water evaporation with mulch: An empirical model to predict cumulative Es (∑Es), developed from the maize experiment with IRWH system, was evaluated as influenced by both organic mulch ("*dry-mulch*") and shading ("*green-mulch*") on the basin area and across various portions of the runoff area. Results from the basin area gave the highest seasonal ∑Es of 173.4 and 152.2 mm in the narrow RSL-1 and lowest values were 62.2 and 54.6 mm for the wide RSL-3, for first and second growing season, respectively. This meant that ∑Es from a basin area beneath a maize canopy was proportional to about 61% of the rainfall for the narrow compared to 22% for the wide treatments, due to the effect of less shading in the basin area for the narrow treatment. On the runoff strip, the highest ∑Es was found from bare soils with various shading effects; and in contrast the fully mulched (96%) surface was the most effective in reducing soil evaporation. Thus, the evaporative water loss as a proportion of seasonal rainfall was about 64% from the bare treatments, and as low as 30% for full mulch or shade from the plant rows. Therefore it can be summarized, that either "*dry-mulch*" beneath or "*green mulch*" of a maize canopy can successfully reduce the Es loss, making the water saved water available for transpiration by the plants, which is a good reason to promote improved water conservation strategies.

Water balance and rainwater productivity: A soil water balance was quantified for each component – measured precipitation (P), estimated runoff (Ro), calculated rainfall canopy interception (RCI), measured change in soil water storage (ΔS), estimated soil water evaporation (Es), with drainage (D) assumed to be negligible, such that transpiration (Ev) could be calculated as a residual. Hence, it was possible to quantify the efficiency of water use such as rain storage efficiency (RSE), precipitation use efficiency (P_{gf}), water use efficiency (WUE_{ET}), water productivity (WP_{Ev}) and rain water productivity (RWP). The results, taking into consideration critical stress periods during the sensitive reproductive growth stages, showed higher plant available water on narrow runoff strips, while the wide treatments were depleted nearly to the lower limit. From the results of ET, it was revealed that surface treatments (mulch and shading) were successful in minimizing the unproductive loss of water through Es. This meant that a smaller portion of ET was lost to Es compared to Ev, i.e. Ev/ET ≫ Es/ET under higher mulch cover while for bare and lower mulch cover Ev/ET ≪ Es/ET. The mean Ev/ET was in the range of 39% – 70% for different RSL treatments, where as Es/ET was 30% - 61%. The performance of the grain yield did not show significant differences across various mulch levels on the runoff strip, but the narrow runoff (RSL-1) showed higher yield than wide RSL-3. The performance of the harvest index (HI) is slightly variable across treatments, mainly due to more runoff water for yield being accumulated from bare plots than mulch cover plots, as higher mulch also conserves water by suppressing Es. Therefore the comparison in terms of the efficient use of rainwater and water productivity was of paramount importance in evaluating the technique of IRWH.

The rain storage efficiency (RSE) gave a higher value for wide RSL compared to narrow, but mulch effect was not considered. In the case of PUE_{gf}, the narrow RSL showed slightly better PUE_{gf} than the wide RSL due to the effect of full shading that reduce the Es losses thus allowing for more water to be transpired. For mean grain yield per unit ET (WUE_{ET}) and Ev (WP_{Ev}) the RSL-2 and RSL-1.5 at low mulch levels (bare to ML39%) had significant higher values than both narrow RSL-1 and RSL-3 treatments. The lowest value for converting water into yield was obtained from wide runoff strip with full mulch cover during growing season 2008/09. In general it would be desirable to have long-term yield prediction together with the water use in order to evaluate management practices under the technique of IRWH in the semi-arid areas.

11.2 Profile characterization and energy balance components

The IRWH tillage system has a reasonably sparse maize canopy as it is planted in alternating wide or narrow rows with a runoff strip between them. These features create an unusual crop canopy with many variations in air movement and radiation absorption and reflection which are related to both the heat and water vapour transfer processes. Micrometeorologists use energy balance measurements to calculate latent heat of evaporation and thus predict ET. However, as the IRWH system modifies the energy balance it was important to understand whether it is favourable for transpiration, crop growth and production. The effects of the surface cultural management practices on energy exchange also needed to be quantified. In the Chapter 8 quote by David Gates, the pioneer in field plant atmosphere biophysics, it states very clearly that an understanding of the continuum of space describing the "environment" where a plant must exchange energy to grow, is a necessity when considering plant function and process. This principle was applied in these micrometeorological studies of IRWH system, whereby the fundamental concept of vertical profile characterization within and above canopies was needed together with the energy balance when partitioning energy in plant canopies and at the soil surface. This lead to a core topic of biophysics – latent heat exchange and coupling of mass and energy transfer within/above the canopy in wide and narrow strips. In this study therefore, the vertical profile characterization was fundamental to examining the effects of IRWH on microclimate within/above maize canopy and partitioning of available energy into sensible and latent heat.

Within canopy profiles: Variation in canopy structure of the maize crop under IRWH had a major influence on vertical distribution of meteorological variables and their role in the energy fluxes to/from the canopy and soil surface. Results showed statistical differences of water vapour pressure (ea) and virtual potential temperature (θv) between the wide and narrow strips. The vertical profiles showed a sigmoid-shaped ea with decrease from mid to lower canopy in narrow and from lower to upper canopy in wide strips. The case of θv profile showed no difference in middle section between wide and narrow strips but the lower and upper portion had lower θv in narrow compare to wide strips. These findings suggest that the equilibrium layer above the maize canopy under IRWH tillage system varies in response to wind speed and caused more eddies and mixing in a wide runoff strips compared to narrow strips. This result confirmed that the effect of wind on water vapour removal decreased downward as wind flow transfers within the canopy, which has an influence on the resistance of the boundary layer and canopy and soil surface resistance. This confirmed the dependence of ea concentration on the wind flow variation within the canopy for both wide and narrow strips.

Under windy conditions, the value of ea within the canopy increased at higher wind speeds reaching a plateau of 1.6 KPa at winds in range of 1.4 - 1.8 m s^{-1} and 2.0 - 2.4 m s^{-1} for wide and narrow RSL treatments. This provides a clear indication that the wide strips were supplying more drying power with a higher atmospheric evaporative demand than for narrow strips. The relationship of θv and ea also showed that with an increase in temperature the concentration of ea within canopy decreases sharply. Nevertheless, the wind profile within the wide strips causes more eddies compared to narrow strips. As a result ET increases dramatically with increase turbulence but also depends on the magnitude of humidity and temperature profiles within the canopy. On the contrary, under weak wind conditions the air within the canopy may not move very much, raising the humidity of air around the canopy as less saturated air was being replaced by drier air. To conclude the relationship of climatic variables within the plant canopy influence ET under the tillage system of IRWH, the key factor being the movement of air and turbulence that is a function of wind speed which varied according to the length of runoff strips.

Above canopy profile characterization and VPD relations: As the air flow within and above the canopy changed the surface heat flux in wide and narrow runoff strips, this explains the development of boundary layer approximation. The results showed the wind speed of the profile increased with height. The local advection was manifested by distorted vertical temperature and humidity profiles that had evidence of the formation of a bulge at the equilibrium height (just above the canopy) and in the thermal boundary layer at about 1.5hc height. This indicated a depletion of energy from the warm, dry, advective air directed towards the runoff strip and upward flux of water vapour within the internal boundary layer due to evaporating maize canopy. The presence of the local advection in IRWH could be a common phenomenon causing variations in water vapour removal under the heterogeneous nature of IRWH tillage system. However, it depends on the size of the runoff area, degree of wetness of the soil surface and is more likely with higher temperatures and under windy conditions. In general, advection is more pronounced in wide runoff strips relative to narrow strips. Since, the enhancement of ET during advective conditions was expected to decrease water use efficiency as sensible heat energy supplied by advection can evaporate water but cannot contribute to yield. Therefore, it is important to estimate the total energy used by ET, on at least an hourly basis, coming from sensible heat advection in wide and narrow strips under IRWH tillage system.

From the profile of θv and ea it is possible to derive an expression for thermal stability stratification which was shown to be influence by the canopy structures (wide or narrow RSL) under wet and dry conditions. On wet days, the mixed air layers just above the canopy grow rapidly and it may continue throughout the day, whereas, on dry days, the growth of the mixing layer was very weak. However, in general on wide strips within the canopy the profile was relatively more stable or near neutral condition than for narrow strips. This tends to make the vertical turbulence over wide runoff strips are greatly suppressed as compared to narrow strips. It was also noted that, due to surface heating on the wide runoff strip, there could be unstable conditions shortly after sunrise which warmed the lowest layer above the canopy. Results also showed that, vapour pressure deficit (VPD) and temperatures were strongly correlated with wind speed. This is a clear indication of dependence of VPD on wind speed at all heights in the profiles between the rows of the IRWH system. From the present study, it was suggested that, profile characteristics within/above plant canopies are playing a great role in determining the VPD and consequently, help to determine the transpiration rate of the crop.

Comparison of available energy: The aerodynamic - energy balance method is not only an approach to quantify the fluxes of LE and Hs, but an complex interesting experiment due to the heterogeneous nature of the alternative basin and runoff strip areas of the IRWH system. Thus, the present research on the energy balance components opens a new chapter in the studies of IRWH in a semi-arid area. The main focus of the energy balance studies using micrometeorological measurements was to address differences in available energy for ET between wide 3 m and narrow 1.5 strips of the IRWH plots. The results indicated that the LE was dominant and higher in wide compared to narrow RSL during both dry and wet conditions. However, Hs showed lower values on wide runoff strips during wet conditions due to the advective effect of the runoff area. Therefore, the wide runoff strip with a higher Bain leaf area ratio (BLAR) had more ET and used more energy on evaporating water compared to narrow runoff with a lower BLAR. From the results, the available energy (Rn-G) converted into LE were represented by about 59% & 64% on dry days and 72% & 63% on wet days for wide and narrow RSL, respectively. Hence, the ET values around midday (11:00 – 15:00) were estimated as 1.2 mm and 2.51 mm for dry and wet conditions, respectively. Wide runoff strips converted the higher available energy more efficiently into a higher biomass production. During wet days, the wide RSL used more available energy, while the narrow RSL response to the available energy was stronger during dry compared to wet days.

In general from this study, it can be concluded that, water scarcity in dryland agriculture cannot not be sufficiently well explained *only* by soil water balance component studies, as it is to a large extent driven by available energy and partitioning of energy balance components according to water management strategies. When quantifying and evaluating the causes behind and the effects of availability of energy one should take into consideration the four interacting energy balance components (Rn, G, LE and Hs) in the tillage of IRWH as well. In order to increase water productivity, it seems clear that both the soil water balance and the available energy during all growth stages have to be improved. The challenge should be addressed on the basis of an integrated approach to water and energy resources in order to develop comprehensive management strategies so that: (i) the best possible use of limited water for rainfed agriculture in semi-arid areas is made, i.e. minimize unproductive water losses, especially by limiting runoff and evaporation from soil; and (ii) other critical point, from an micrometeorological point of view, is that the spatial and temporal profile characterization and accurate estimation of latent and sensible heat fluxes for wide and narrow runoff strips is necessary in order to evaluate strategies and optimise water and energy use.

Future studies

The growing interest in the application of integrated studies of soil water balance and micrometeorological parameters for alternative evaluations is a noteworthy experience in IRWH. However, many questions remain to be answered. Fully understanding the effect of surface treatments on planting date and density can be achieved by coupling with a crop model like APSIM in order to run long-term risk analysis. Moreover, to do such research on conservation agriculture system will contribute to creating a technique to partition the ET losses from the canopy and soil surface on wide and narrow runoff strips. This question will be attempting to create selection criteria to assess the optimum surface treatments and appropriate cultural management for maize production under IRWH for each specific ecotope.

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Appendices

Appendix 1.1 Comparison of selected research studies with present study on IRWH. Each number in the column A, B & C corresponds to study description; accordingly, column D describe the measurement s performed and column E describe general evaluation of the study.

(A) **1.Country** **2. Locality** **3. Author** **4. Year**	**(B)** **1. Climate** **2. Crop** **3. Mulch** **4. RSL**	**(C)** **1. Soil** **2.Clay%** **3. Slope**	**(D) Measurements / Estimations (+ = performed and − = not performed)**																				**(E)** **Evaluate Param.**
			Soil Water Balance Comp.						**Micromet/Prof.**			**Energy Fluxes**				**Crop Parameter**			**Water Use**				
			Ro	***Es***	***Ev***	***ET***	***ΔS***	***D***	***T***	***RH***	***u***	***Hs***	***λE***	***G***	***Rn***	***Y***	***ADM***	***TDM***	***PUE***	***WUE***	***RWP***	***WP***	
1. RSA **2**.Tabanchu **3**. Hensley **4**. 2000	**1**.Semi-arid **2**. Maize, beans Sunfl. **3**.organic **4**.2m	**1**.Clay **2**.17%-45% **3**.2%	+	+	+	+	+	+	−	−	−	−	−	−	−	+	+	−	+	+	+	−	**Yield** **Ro** **model**
1. RSA **2**. Glen **3**. Botha *et al.,* **4**. 2003	**1**.Semi-arid **2**.maize bean, sunflower **3**.Various **4**.2 m	**1**.Clay **2**.45%, 38% **3**.1%	+	+	+	+	+	+	−	−	−	−	−	−	−	+	+	−	+	+	+	+	**Yield,** **WB** **Es model**
1. Mexico **2**.-Texcoco **3**. Ventura *et al.,* **4**. 2003	**1**. Semi-arid **2**. maize beans **3**. - **4**. -	**1**. clay loam **2**.60% **3**. -	+	+	−	+	+	+	−	−	−	−	−	−	−	+	−	−	+	+	−	−	**Yield**
1. China **2**.- Loess **3**. Gabriels *et al.,* **4**. 2003	**1**.Sub-humid to arid **2**. maize peanuts wheat	**1**. clay loam **2**.14% **3**. -	−	−	−	−	−	−	−	−	−	−	−	−	−	+	−	−	+	−	−	−	**Yield**
1. RSA **2**. Pretoria **3**. Ibraimo **4**. 2011	**1**.Semi-arid **2**. maize **3**.organic **4**. 1, 2, 3 m	**1**.Semi -arid **2**.Clay loam **3**. 6%	+	−	−	+	+		−	−	−	−	−	−	−	+	−	−	+	+	−	−	**WB** **Yield**
1.RSA **2**.Bainsvile / Parades **3**.Zerizghy **4**. 2011	**1**.Semi-arid **2**. fallow **3**.Bare **4.** 1,2,3 m	**1**.Sand Clay **2**.8.5% / 18% **3**.1%	+	+	−	+	+	+	−	−	−	−	−	−	−	−	−	−	−	−	−	−	**Fallow** **WB**
Current Study RSA Bainsvlei ecotope	**1.Semi-arid** **2. maize** **3ML(0-96%)** **4.1,1.5,2,3m**	**1. fine sandy loam** **2.8.5%** **3. 1%**	+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	−	+	+	+	+	**Yield** **Ro, Es, EB, WB model**

where *Ro=Runoff, Es=Evaporation, Ev=Transpiration ET= Evapotranspiration, ΔS=water content, T=Temperature, RH=relative humidity, u=Wind, Hs=sensible heat flux, λE=Latent heat flux, G=Soil heat flux, Rn Net radiation, Y=yield, ADM Above ground dry matter, TDM=Total dry mater, PUE=precipitation use efficiency, WUE=water use efficiency, RWP=Rain water productivity, WP =Water productivity and RSL= Runoff stripe length.*

Appendix 2.1 Profile description of the Bainsvlei form soil (Chimungu 2009)

Map/photo :	**2926 Bloemfontein**	**Soil form and family:**	**Bainsvlei *Amalia***
Latitude + Longitude:	29: 1‟ 00‟‟/26: 08‟ 00‟‟	Surface rockiness:	None
Altitude:	1354 m	Occurrence of flooding:	None
Terrain unit:	Lower foot slope	Wind erosion:	Slight wind
Slope:	1%	Water erosion:	None
Slope shape:	Straight	Vegetation/Land use:	Agronomic field crops
Aspect:	North-west	Water table:	None
Microrelief:	None	Described by:	M. Hensley & J. Chimungu
Parent Material Solum:	Origin single, aeolian	Date described:	14/06/09
Underlying Material:	Sandstone (Feldspathic)	Weathering of underlying material:	Weak physical to moderate chemical
Alteration of underlying material:	Ferruginised		

Horizon	Depth (mm)	Description	Diagnostic horizon
A	**0-250**	Moist state; dry colour: yellowish red (5YR5/6); moist colour: reddish brown (5YR4/4); texture: fine loamy sand; structure: apedal massive; consistence: friable; few fine normal pores; water absorption: 1 second; few roots; gradual smooth transition.	Orthic
B1	**250-420**	Moist state; dry colour: red (2.5YR4/8); moist colour: red (2.5YR4/6); texture: fine sandy loam; structure: apedal massive; consistence: friable; few fine normal pores; water absorption: 1 second; few roots; gradual smooth transition.	Red apedal
B2	**420-700**	Moist state; dry colour: yellowish red (5YR5/8); moist colour: red (2.5YR4/6); texture: fine sandy loam; few fine faint black illuvial humus mottles; structure: apedal massive; consistence: friable; common fine normal pores; water absorption: 1 second; few roots; gradual wavy transition.	Red apedal
B3	**700-1200**	Moist state; dry colour: yellowish red (5YR4/6); moist colour: reddish brown (5YR4/4); texture: fine sandy clay loam; common fine faint black illuvial humus mottles; structure: apedal massive; consistence: slightly firm; common fine normal pores; water absorption: 1 second; clear wavy transition.	Red apedal
B4	**1200-1450**	Moist state; dry colour: strong brown (7.5YR5/8); moist colour: strong brown (7.5YR5/6); texture; fine sand; few fine faint black illuvial humus mottles; structure: apedal massive; consistence: friable; water absorption: 1 second; few roots; clear wavy transition.	Non diagnostic; yellow brown Aeolian sand
B5	**1450-1850**	Moist state; moist colour: strong brown (7.5YR4/6); texture: fine sandy loam; many medium distinct grey and yellow reduced iron oxide mottles; many medium distinct red and black oxidised iron oxide mottles; structure: apedal massive; consistence: friable; water absorption: 1 second(s); few roots; gradual smooth transition.	Soft plinthic
C	**1850-2220**	Similar to B5 with patches of weathered feldspathic sandstone; colour of mottles similar to B5 but more prominent.	

Appendix 2.2 Summary of chemical and physical characteristics of a Bainsvlei form soil. (Chimungu 2009)

	Physical properties					
	A	**B1**	**B2**	**B3**	**B4**	**B5**
Coarse sand (2 - 0.5 mm) (%)	0.4	0.3	0.3	0.3	0.3	0.4
Medium sand (0.5 - 0.25) (%)	7.1	5.2	5.4	4.1	3.3	7.1
Fine sand (0.25 - 0.106 mm) (%	61.4	55.1	53.8	44.9	64.3	61.4
Very fine sand (0.106 - 0.53mm) (%)	16.8	15.1	15.5	18.0	17.3	16.8
Silt (%)	4.0	4.0	6.0	8.0	4.0	4.0
Clay (%)	8.0	18.1	18.0	22.1	8.1	8.0
Bulk density (Mg m^{-3})	1.66	1.68	1.66	1.67	1.68	1.66
	Chemical properties					
pH (water)	5.2	5.1	6.3	6.1	6.7	6.5
Ca ($cmol_c.kg^{-1}$)	7.2	15.3	11.0	16.2	11.3	11.1
Mg ($cmol_c.kg^{-1}$)	4.3	10.2	10.4	9.4	11.7	10.3
K ($cmol_c.kg^{-1}$)	2.5	3.6	2.2	2.6	2.1	2.0
Na ($cmol_c.kg^{-1}$)	4.1	3.8	2.7	2.5	2.4	2.7
Clay –S value	-	Eutrophic*	-	-	-	-

Appendix 3.1 Rainfall characteristics in-terms of rainfall event amount, duration and intensity for growing season 2008/09 at Kenilworth Experimental Farm, (Pi = peak intensity).

GS	DAP	Event Amount (mm)	Event Duration (min)	Event Pi (mmh^{-1})	Event Mean Intensity (mmh^{-1})	Event Median Intensity (mmh^{-1})
GS-I	**1**	6.6	*	*	*	*
	7	15.7	*	*	*	*
	12	16.6	*	*	*	*
	16	2.5	*	*	*	*
	23	18.3	340	30	9.0	6.0
	24	1.5	260	1.2	0.8	0.6
	33	13.3	210	46.8	13.0	5.4
	34	0.8	110	1.2	1.2	1.2
	35	0.3	35	0.02		
	37	2.9	60	6	5.4	5.4
	38	1.1	40	2.4	1.8	1.8
	38	2.5	145	4.8	2.1	1.2
	41	25.9	1200	14.4	3.5	2.4
	42	1.1	125	1.2	0.8	1.2
	45	5.4	25	20.4	10.2	10.2
GS-II	**49**	1.7	35	8.4	4.3	4.3
	51	2.2	120	3.6	2.4	2.4
	53	2	175	7.2	3.7	3.0
	53	0.4	90	1.2	0.9	0.9
	54	2.9	165	1.2	1.2	1.2
	55	0.9	40	2.4	1.8	1.8
	55	8.9	400	4.8	2.8	2.4
	56	1	265	2.4	0.6	0.2
	57	1.7	120	6	4.4	6.0
	58	3	170	6		
	58	0.8	50	2.4	1.4	1.4
	58	1.6	15	16.8		
	58	4.5	205	7.2	3.6	3.0
	59	12.4	125	30	12.7	8.4
	60	0.3	60	1.2	0.7	0.7
	62	3.3	155	3.6	2.5	3.6
	63	4.6	55	12	7.2	7.2
	63	0.4	45	1.2		
	64	1.5	130	7.2	3.2	1.2
	69	1.1	55	10		
GS-III	**70**	6.8	170	14.4	4.5	1.2
	70	2.6	75	7.2	3.8	2.4
	81	0.8	15	6		
	81	7.1	45	44.4		
	86	10.6	140	24	9.4	4.8
	97	0.5	10	2.4		
	97	1.3	15	8.4		
	105	10.6	125	24	10.8	8.4
GS-IV	**111**	1.8	190	2.4	1.8	1.8
	127	0.1	5	1.2		
	127	1.5	30	1.5	4.6	1.2
	127	4.6	135	28.8	11.4	4.8
	128	1.2	35	4.8	3.6	3.6
	129	0.4	10	5		
	131	0.3	30	10		
	132	1.1	15	2.4	1.8	1.8
	137	6.2	140	4.8	4.8	4.8
	138	8.5	415	10.8	3.4	1.8
	142	6.4	195	7.2	3.9	3.6
	150	2.1	160	3.6	2.0	2.0
	150	5.6	30	33.6	12.5	3.6
	Total	**249.8**				
	Highest	**25.9**	**1200.0**	**46.8**	**13.0**	**10.2**
	Lowest	**0.1**	**5.0**	**1.2**	**0.6**	**0.2**
	Mean - Observed	**4.5**	**134.8**	**9.8**	**4.5**	**3.2**
	Glen Mean Long-term	**4.3**	**130.0**	**22.5**		

**at the beginning of the experiment the automatic weather station was working.*

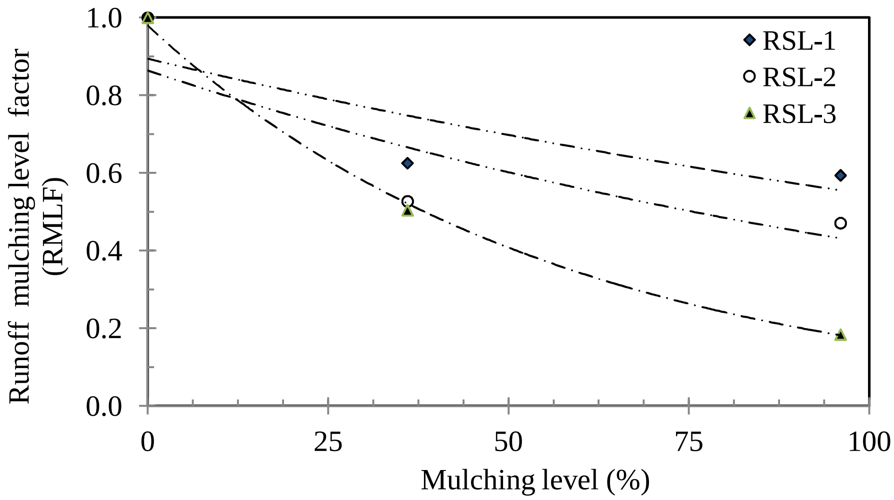
Appendix 4.1 Calculated values of rainfall interception, RCI (mm) for different RSL treatments for each rain event during growing season (2008/09) using equation 4.1. The figures in parenthesis indicate the percentage (%) that canopy interception of the rain event.

Growth stage (GS)		GS-I				GS-II			GS-III			GS-IV	
DAP		**23**	**33**	**37**	**41**	**54**	**58**	**70**	**81**	**86**	**105**	**127**	**138**
RF (mm)		**19.8**	**14.1**	**6.5**	**25.9**	**12.7**	**22.3**	**10.5**	**7.9**	**10.6**	**10.6**	**7.4**	**14.7**
RSL (m)	**1**	0.058 (0.3)	0.069 (0.5)	0.019 (0.3)	0.151 (1.7)	0.470 (3.7)	0.719 (3.2)	0.449 (4.3)	0.353 (4.5)	0.453 (4.3)	0.456 (4.3)	0.333 (4.5)	0.588 (4.0)
	1.5	0.076 (0.2)	0.082 (0.6)	0.013 (0.2)	0.124 (1.4)	0.569 (4.5)	0.854 (3.8)	0.565 (5.4)	0.446 (5.7)	0.569 (5.4)	0.573 (5.4)	0.422 (5.7)	0.732 (5.0)
	2	0.076 (0.4)	0.120 (0.9)	0.019 (0.3)	0.211 (2.2)	0.673 (5.3)	0.994 (4.5)	0.640 (6.1)	0.508 (6.4)	0.645 (6.1)	0.649 (6.1)	0.480 (6.5)	0.824 (5.6)
	3	0.094 (0.05)	0.145 (1.0)	0.019 (0.03)	0.881 (2.5)	0.833 (6.6)	1.205 (5.4)	0.881 (8.4)	0.705 (8.9)	0.887 (8.4)	0.893 (8.4)	0.669 (9.0)	1.118 (7.6)

Appendix 4.2 In-field runoff to rainfall ratio (RR) for runoff strip lengths of 1, 1.5, 2 and 3 m with different mulch cover levels (bare, 39% & 96%) during growing season (2008/09).

Growth stage (GS)		GS-I				GS-II			GS-III			GS-IV	
DAP		**23**	**33**	**37**	**41**	**54**	**58**	**70**	**81**	**86**	**105**	**127**	**138**
RSL-1	ML0%	0.29	0.43	0.14	0.12	0.09	0.35	0.24	0.23	0.30	0.40	0.30	0.21
	ML39%	0.22	0.34	0.16	0.11	0.10	0.11	0.10	0.20	0.12	0.18	0.16	0.16
	ML96%	0.18	0.31	0.12	0.11	0.07	0.09	0.13	0.17	0.09	0.23	0.25	0.15
RSL-1.5	ML0%	0.20	0.22	0.05	0.10	0.05	0.16	0.13	0.23	0.12	0.20	0.17	0.15
	ML39%	0.20	0.18	0.08	0.08	0.06	0.13	0.07	0.10	0.08	0.13	0.11	0.10
	ML96%	0.17	0.20	0.10	0.07	0.06	0.09	0.07	0.16	0.07	0.12	0.17	0.10
RSL-2	ML0%	0.16	0.25	0.08	0.08	0.05	0.20	0.18	0.26	0.19	0.32	0.29	0.30
	ML39%	0.14	0.12	0.08	0.07	0.08	0.13	0.08	0.08	0.04	0.11	0.14	0.07
	ML96%	0.12	0.16	0.11	0.07	0.05	0.10	0.07	0.07	0.05	0.07	0.14	0.04
RSL-3	ML0%	0.12	0.14	0.04	**NA**	0.05	**NA**	0.10	0.25	0.21	0.32	0.20	0.16
	ML39%	0.09	0.10	0.04	0.03	0.03	0.14	0.03	0.04	0.02	0.08	0.13	0.03
	ML96%	0.09	0.06	0.02	0.00	0.00	0.00	0.00	0.03	0.00	0.04	0.05	0.01

Appendix 4.3 Runoff mulch level factor (RMLF) as a function of mulching level (%) cover for three runoff strip length



.

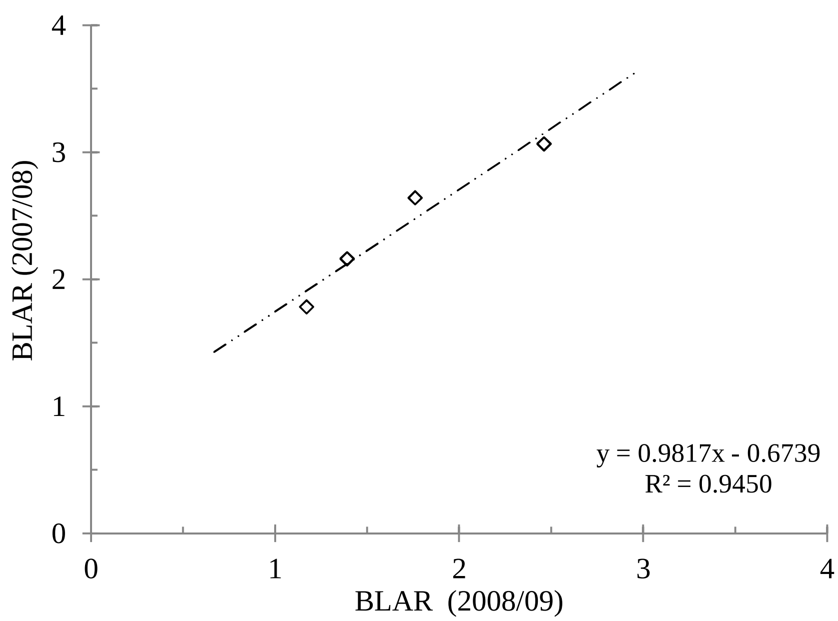
RSL-1: $RMLF = 0.8942e^{-0.005ML}$ (R^2=0.68)

RSL-2: $RMLF = 0.8640e^{-0.007ML}$ (R^2=0.74)

RSL-3: $RMLF = 0.9795e^{-0.018ML}$ (R^2=0.99)

where RMLF= runoff mulching level factor, $\left(RMLF = \frac{\sum Ro_{(mulched)}}{\sum Ro_{(bare)}}\right)$ and ML = percentage of mulching level cover for all of the rain events during 2008/09 . The calculations were made on three runoff strip lengths (RSL-1, 2 and 3m).

Appendix 6.1 Relationship of BLAR for all RSL treatments (n=4) between 2007/08 and 2008/09 cropping season at flowering (65 DAP)



Appendix 6.2 Seasonal estimation of *Es* in the basin for growing season 2007/08 and 2008/09

Cropping season	RSL treatments	Growth stage ∑Es (mm)				Growing period ∑ Es (mm)	Es % of rainfall	Red. in Es (%) (1-(∑Es/∑$_{Epot}$)
		GS-I	GS-II	GS-III	GS-IV			
2007/08	RSL-1	60.9	28.0	53.4	31.1	173.4	61.4	63.9
	RSL-1.5	48.3	22.3	42.4	24.7	137.6	48.7	71.4
	RSL-2	37.0	17.1	32.5	18.9	105.6	37.4	78.1
	RSL-3	21.8	10.1	19.2	11.1	62.2	22.0	87.1
	Mean	**42.0**	**19.4**	**36.9**	**21.5**	**119.7**	**42.4**	**75.1**
2008/09	RSL-1	72.6	23.8	35.3	20.5	152.2	60.9	76.9
	RSL-1.5	57.6	18.9	28.0	16.3	120.7	48.3	81.7
	RSL-2	44.2	14.5	21.5	12.5	92.6	37.1	85.9
	RSL-3	26.0	8.5	12.7	7.4	54.6	21.9	91.7
	Mean	**50.1**	**16.4**	**24.4**	**14.2**	**105.0**	**42.0**	**84.0**

Appendix 6.3 Seasonal estimation of *Es* on the runoff area for growing season 2008/09

Canopy shade	Mulch level (t ha^{-1})	Growth stage ∑Es (mm)				Growing period (mm)	Es% of rainfall	Reduction in Es (%) (1-(∑Es/∑$_{Epot}$)
		GS-I	GS-II	GS-III	GS-IV			
Full canopy shade	0 (Bare)	74.1	24.3	36.1	21.0	155.5	62.2	76.4
	1 (12%)	69.4	22.8	33.8	19.6	145.6	58.3	77.9
	2 (39%)	57.6	18.9	28.0	16.3	120.7	48.3	81.7
	3 (64%)	47.3	15.5	23.0	13.4	99.2	39.7	84.9
	5 (96%)	33.9	11.1	16.5	9.6	71.1	28.5	89.2
Partial canopy shade	0 (Bare)	76.5	25.1	37.2	21.6	160.4	64.2	75.6
	1 (12%)	71.8	23.6	34.9	20.3	150.5	60.3	77.1
	2 (39%)	59.9	19.7	29.1	16.9	125.7	50.3	80.9
	3 (64%)	49.7	16.3	24.2	14.0	104.2	41.7	84.2
	5 (96%)	36.3	11.9	17.6	10.3	76.1	30.5	88.4
Unshaded	0 (Bare)	78.9	25.9	38.4	22.3	165.4	66.2	74.9
	1 (12%)	74.1	24.3	36.1	21.0	155.5	62.2	76.4
	2 (39%)	62.3	20.4	30.3	17.6	130.7	52.3	80.1
	3 (64%)	52.1	17.1	25.3	14.7	109.2	43.7	83.4
	5 (96%)	38.6	12.7	18.8	10.9	81.0	32.4	87.7

Appendix 6.4 Seasonal estimation of *Es* on the runoff area for growing season 2007/08

Canopy shade	Growth stage ∑Es (mm)				Growing period (mm)	Es% of rainfall	Reduction in Es (%) (1-(∑Es/∑$_{Epot}$)
	GS-I	GS-II	GS-III	GS-IV			
Full canopy shade	60.9	28.0	53.4	31.1	173.4	61.4	63.95
Partial canopy shade	64.2	29.6	56.3	32.8	182.8	64.7	61.99
Unshaded	66.1	30.5	58.1	33.8	188.5	66.7	60.81

Appendix 7.1 Summary of water balance components sheet for cropping season 2008/09 for different growth stages under different surface treatments (RSL and ML) for Kenilworth Bainsvlei ecotope.

RSL		**RSL-1**					**RSL-1.5**					**RSL-2**					**RSL-3**				
ML		**0%**	**12%**	**39%**	**64%**	**96%**	**0%**	**12%**	**39%**	**64%**	**96%**	**0%**	**12%**	**39%**	**64%**	**96%**	**0%**	**12%**	**39%**	**64%**	**96%**
P (mm)	**GS-I**	114.5					114.5					114.5					114.5				
	GS-II	64.6					64.6					64.6					64.6				
	GS-III	30.9					30.9					30.9					30.9				
	GS-IV	39.8					39.8					39.8					39.8				
	GP	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**
±Ro (mm)	**GS-I**	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	GS-II	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	GS-III	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	GS-IV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	GP	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
RCI (mm)	**GS-I**	0.30	0.30	0.30	0.30	0.30	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.33	0.33	0.33	0.33	0.33
	GS-II	1.64	1.64	1.64	1.64	1.64	1.99	1.99	1.99	1.99	1.99	1.54	1.54	1.54	1.54	1.54	1.95	1.95	1.95	1.95	1.95
	GS-III	1.26	1.26	1.26	1.26	1.26	1.59	1.59	1.59	1.59	1.59	1.20	1.20	1.20	1.20	1.20	1.66	1.66	1.66	1.66	1.66
	GS-IV	0.92	0.92	0.92	0.92	0.92	1.15	1.15	1.15	1.15	1.15	0.87	0.87	0.87	0.87	0.87	1.19	1.19	1.19	1.19	1.19
	GP	**4.12**	**4.12**	**4.12**	**4.12**	**4.12**	**5.02**	**5.02**	**5.02**	**5.02**	**5.02**	**3.89**	**3.89**	**3.89**	**3.89**	**3.89**	**5.1**	**5.1**	**5.1**	**5.1**	**5.1**
ΔS (mm)	**GS-I**	-44.8	-32.9	-15.5	-20.7	-9.4	-14.3	-36.5	5.3	-52.7	-9.3	-28.9	-30.5	-32.5	-17.9	-13.1	-31.6	-27.5	-6.7	-13.9	-6.2
	GS-II	19.0	46.0	5.2	19.4	19.5	26.1	-6.2	-11.4	-8.9	-5.6	5.2	1.9	4.8	16.7	25.7	5.7	17.3	-8.5	22.2	37.8
	GS-III	79.9	71.9	79.0	82.1	46.9	7.7	19.1	21.2	32.9	28.0	43.6	-1.2	-7.4	-7.8	27.1	52.5	28.6	43.4	-7.5	32.0
	GS-IV	-12.4	-19.8	-29.9	-50.4	0.2	-21.4	4.7	-2.1	-29.4	-40.9	-25.5	-11.5	-5.6	-0.5	-6.0	**-4.7**	**11.9**	**34.9**	**-0.3**	**0.2**
	GP	**41.6**	**65.2**	**38.8**	**30.3**	**57.2**	**-1.9**	**-18.9**	**13.0**	**-58.2**	**-27.8**	**-5.6**	**-41.3**	**-40.8**	**-9.5**	**33.8**	**21.9**	**30.2**	**63.2**	**0.5**	**63.9**
D		**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
ET Resd. (mm)	**GS-I**	79.6	81.3	98.7	93.5	104.8	105.6	99.6	119.5	73.7	104.9	101.4	95.7	80.9	86.6	92.7	86.4	81.2	95.2	89.4	98.6
	GS-II	81.9	108.9	68.1	82.4	82.5	88.7	56.4	51.2	53.7	57.0	59.3	56.6	61.0	73.9	84.0	59.0	71.5	47.4	79.1	95.6
	GS-III	109.5	101.5	108.7	111.7	76.5	37.0	55.3	55.5	65.4	57.3	69.0	41.9	38.9	33.8	54.5	77.5	53.9	69.6	30.3	59.1
	GS-IV	31.9	28.1	18.4	16.9	39.1	21.1	43.4	42.4	22.8	12.9	22.8	29.9	29.1	35.6	32.0	28.2	45.3	69.3	34.8	35.8
	GP	**303.0**	**319.8**	**293.9**	**304.5**	**302.9**	**252.4**	**254.7**	**268.7**	**215.6**	**232.1**	**252.5**	**224.1**	**209.8**	**229.9**	**263.1**	**251.1**	**251.9**	**281.5**	**233.6**	**289.1**
Es (mm)	**GS-I**	73.4	71.0	65.1	59.9	53.2	65.9	63.5	57.6	52.4	45.7	65.7	62.6	54.7	47.8	38.9	64.5	60.9	52.1	44.4	34.3
	GS-II	24.1	23.3	21.4	19.7	17.5	21.6	20.8	18.9	17.2	15.0	21.6	20.5	17.9	15.7	12.8	21.2	20.0	17.1	14.6	11.3
	GS-III	35.7	34.5	31.6	29.1	25.9	32.0	30.9	28.0	25.5	22.2	32.0	30.4	26.6	23.3	18.9	31.4	29.6	25.3	21.6	16.7
	GS-IV	20.7	20.1	18.4	16.9	15.0	18.6	17.9	16.3	14.8	12.9	18.6	17.7	15.5	13.5	11.0	**18.2**	**17.2**	**14.7**	**12.5**	**9.7**
	GP	**153.8**	**148.9**	**136.5**	**125.7**	**111.6**	**138.1**	**133.1**	**120.7**	**110.0**	**95.9**	**137.8**	**131.2**	**114.7**	**100.3**	**81.6**	**135.2**	**127.8**	**109.2**	**93.0**	**71.9**
Ev Resd. (mm)	**GS-I**	6.3	10.3	33.7	33.5	51.6	39.7	36.2	62.0	21.3	59.1	35.7	33.1	26.2	38.8	53.8	21.9	20.3	43.1	45.0	64.3
	GS-II	57.9	85.6	46.8	62.7	65.0	67.1	35.6	32.3	36.5	42.0	37.7	36.1	43.0	58.2	71.2	37.9	51.5	30.3	64.6	84.3
	GS-III	73.8	67.0	77.0	82.5	50.6	5.0	24.4	27.5	39.9	35.1	37.0	11.5	12.3	10.5	35.6	46.1	24.3	44.3	8.7	42.4
	GS-IV	11.2	8.0	0.0	0.0	24.0	2.5	25.4	26.1	7.9	0.0	4.2	12.2	13.6	22.1	21.0	**9.9**	**28.0**	**54.6**	**22.3**	**26.1**
	GP	**149.2**	**171.0**	**157.5**	**178.8**	**191.3**	**114.3**	**121.6**	**147.9**	**105.6**	**136.2**	**114.6**	**92.9**	**95.1**	**129.5**	**181.5**	**115.8**	**124.2**	**172.3**	**140.6**	**217.1**

NB. P = cropping season rainfall, ±Ro = Run-on/Runoff, RCI = rainfall canopy interception, Δ S= change in soil water content, D = drainage, ET = Resd. Evapotranspiration calculated as residual, Es = soil water evaporation and Ev Resd. = transpiration calculated as residual of ET. All components are computed in mm.

Appendix 7.2 RSL-1 treatment **w**ater balance components sheet for cropping season 2008/09 for different growth stages under different mulch level treatments (ML) for Kenilworth Bainsvlei ecotope.

RSL-1		BA					RA1				
ML		0%	12%	39%	64%	96%	0%	12%	39%	64%	96%
P (mm)	GS-I	114.5					114.5				
	GS-II	64.6					64.6				
	GS-III	30.9					30.9				
	GS-IV	39.8					39.8				
	GP	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**
±Ro (mm)	GS-I	17.4	15.8	12.9	10.9	9.5	-17.4	-15.8	-12.9	-10.9	-9.5
	GS-II	9.8	9.0	7.3	6.2	5.4	-9.8	-9.0	-7.3	-6.2	-5.4
	GS-III	4.7	4.3	3.5	3.0	2.6	-4.7	-4.3	-3.5	-3.0	-2.6
	GS-IV	6.1	5.5	4.5	3.8	3.3	-6.1	-5.5	-4.5	-3.8	-3.3
	GP	**38.0**	**34.6**	**28.2**	**23.9**	**20.7**	**-38.0**	**-34.6**	**-28.2**	**-23.9**	**-20.7**
RCI (mm)	GS-I	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	GS-II	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64	1.64
	GS-III	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26	1.26
	GS-IV	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
	GP	**4.12**	**4.12**	**4.12**	**4.12**	**4.12**	**4.12**	**4.12**	**4.12**	**4.12**	**4.12**
ΔS (mm)	GS-I	-46.5	-44.8	-23.6	-27.5	-7.4	-43.1	-21.0	-7.3	-13.9	-11.4
	GS-II	10.3	45.7	6.2	20.7	28.1	27.6	46.2	4.1	18.2	10.9
	GS-III	92.5	91.0	84.3	77.1	37.4	67.3	52.8	73.8	87.0	56.4
	GS-IV	-35.4	-41.8	-38.2	-39.3	1.3	10.5	2.2	-21.6	-61.6	-0.9
	GP	**20.9**	**50.2**	**28.6**	**31.0**	**59.4**	**62.3**	**80.2**	**49.0**	**29.7**	**55.0**
D		**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
ET Resd. (mm)	GS-I	85.1	85.2	103.5	97.6	116.3	74.1	77.4	94.0	89.4	93.4
	GS-II	83.1	117.7	76.5	89.9	96.4	80.7	100.2	59.8	74.9	68.5
	GS-III	126.8	124.9	117.4	109.7	69.6	92.2	78.2	99.9	113.7	83.4
	GS-IV	20.5	20.5	20.5	20.5	43.5	43.3	35.6	16.3	13.4	34.6
	GP	**315.6**	**348.3**	**317.9**	**317.6**	**325.8**	**290.4**	**291.3**	**270.0**	**291.4**	**280.0**
Es (mm)	GS-I	72.6	72.6	72.6	72.6	72.6	74.1	69.4	57.6	47.3	33.9
	GS-II	23.8	23.8	23.8	23.8	23.8	24.3	22.8	18.9	15.5	11.1
	GS-III	35.3	35.3	35.3	35.3	35.3	36.1	33.8	28.0	23.0	16.5
	GS-IV	20.5	20.5	20.5	20.5	20.5	21.0	19.6	16.3	13.4	9.6
	GP	**152.2**	**152.2**	**152.2**	**152.2**	**152.2**	**155.5**	**145.6**	**120.7**	**99.2**	**71.1**
Ev Resd. (mm)	GS-I	12.5	12.7	30.9	25.0	43.7	0.0	8.0	36.4	42.1	59.5
	GS-II	59.3	93.8	52.6	66.0	72.6	56.4	77.4	40.9	59.4	57.4
	GS-III	91.6	89.6	82.1	74.4	34.3	56.1	44.4	71.9	90.7	67.0
	GS-IV	0.0	0.0	0.0	0.0	23.0	22.4	16.0	0.0	0.0	25.1
	GP	**163.4**	**196.1**	**165.7**	**165.5**	**173.7**	**134.9**	**145.8**	**149.2**	**192.2**	**208.9**

NB. P = cropping season rainfall, ±Ro = Run-on/Runoff, RCI = rainfall canopy interception, Δ S= change in soil water content, D = drainage, ET = Resd. Evapotranspiration calculated as residual, Es = soil water evaporation and Ev Resd. = transpiration calculated as residual of ET. All components are computed in mm.

Appendix 7.3 RSL-1.5 treatment **w**ater balance components sheet for cropping season 2008/09 for different growth stages under different mulch level treatments (ML) for Kenilworth Bainsvlei ecotope.

RSL-1.5		**BA**					**RA1**				
ML		**0%**	**12%**	**39%**	**64%**	**96%**	**0%**	**12%**	**39%**	**64%**	**96%**
P (mm)	**GS-I**	114.5					114.5				
	GS-II	64.6					64.6				
	GS-III	30.9					30.9				
	GS-IV	39.8					39.8				
	GP	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**
±Ro (mm)	**GS-I**	35.8	33.0	27.4	23.2	19.0	-35.8	-33.0	-27.4	-23.2	-19.0
	GS-II	20.6	19.0	15.9	13.5	11.1	-20.6	-19.0	-15.9	-13.5	-11.1
	GS-III	10.0	9.3	7.8	6.6	5.5	-10.0	-9.3	-7.8	-6.6	-5.5
	GS-IV	12.7	11.7	9.8	8.3	6.9	-12.7	-11.7	-9.8	-8.3	-6.9
	GP	**79.1**	**73.0**	**60.9**	**51.6**	**42.5**	**-79.1**	**-73.0**	**-60.9**	**-51.6**	**-42.5**
RCI (mm)	**GS-I**	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29	0.29
	GS-II	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99	1.99
	GS-III	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59	1.59
	GS-IV	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
	GP	**5.02**	**5.02**	**5.02**	**5.02**	**5.02**	**5.02**	**5.02**	**5.02**	**5.02**	**5.02**
ΔS (mm)	**GS-I**	-13.0	-17.3	-10.7	-37.2	-28.8	-15.6	-55.6	21.4	-68.2	10.1
	GS-II	-22.0	-20.1	-29.4	-28.3	-37.0	74.2	7.7	6.6	10.5	25.7
	GS-III	-6.0	-24.4	-19.1	-14.3	8.8	21.4	62.6	61.5	80.1	47.3
	GS-IV	-30.0	-6.6	20.1	-14.9	-55.7	-12.8	16.0	-24.2	-44.0	-26.1
	GP	**-71.0**	**-68.4**	**-39.1**	**-94.7**	**-112.6**	**67.2**	**30.6**	**65.2**	**-21.7**	**56.9**
D		**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
ET Resd. (mm)	**GS-I**	137.0	129.9	130.9	100.2	104.5	74.1	69.4	108.1	47.3	105.3
	GS-II	61.2	61.6	49.1	47.8	36.8	116.2	51.3	53.3	59.6	77.2
	GS-III	33.3	28.0	28.0	28.0	43.6	40.7	82.7	83.0	102.8	71.1
	GS-IV	21.3	43.8	68.5	32.1	16.3	21.0	42.9	16.3	13.4	9.6
	GP	**252.9**	**263.3**	**276.5**	**208.1**	**201.1**	**252.0**	**246.2**	**260.8**	**223.1**	**263.1**
Es (mm)	**GS-I**	57.6	57.6	57.6	57.6	57.6	74.1	69.4	57.6	47.3	33.9
	GS-II	18.9	18.9	18.9	18.9	18.9	24.3	22.8	18.9	15.5	11.1
	GS-III	28.0	28.0	28.0	28.0	28.0	36.1	33.8	28.0	23.0	16.5
	GS-IV	16.3	16.3	16.3	16.3	16.3	21.0	19.6	16.3	13.4	9.6
	GP	**120.7**	**120.7**	**120.7**	**120.7**	**120.7**	**155.5**	**145.6**	**120.7**	**99.2**	**71.1**
Ev Resd. (mm)	**GS-I**	79.4	72.3	73.4	42.6	46.9	0.0	0.0	50.6	0.0	71.4
	GS-II	42.3	42.7	30.2	28.9	17.9	91.9	28.5	34.4	44.0	66.0
	GS-III	5.3	0.0	0.0	0.0	15.6	4.6	48.9	55.0	79.8	54.6
	GS-IV	5.1	27.5	52.2	15.9	0.0	0.0	23.3	0.0	0.0	0.0
	GP	**132.1**	**142.5**	**155.8**	**87.4**	**80.4**	**96.5**	**100.7**	**140.0**	**123.9**	**192.0**

NB. P = cropping season rainfall, ±Ro = Run-on/Runoff, RCI = rainfall canopy interception, Δ S= change in soil water content, D = drainage, ET = Resd. Evapotranspiration calculated as residual, Es = soil water evaporation and Ev Resd. = transpiration calculated as residual of ET. All components are computed in mm.

Appendix 7.4 RSL-2 treatment **w**ater balance components sheet for cropping season 2008/09 for different growth stages under different mulch level treatments (ML) for Kenilworth Bainsvlei ecotope.

RSL-2		**BA**					**RA1**					**RA2**				
ML		**0%**	**12%**	**39%**	**64%**	**96%**	**0%**	**12%**	**39%**	**64%**	**96%**	**0%**	**12%**	**39%**	**64%**	**96%**
P (mm)	**GS-I**			114.5					114.5					114.5		
	GS-II			64.6					64.6					64.6		
	GS-III			30.9					30.9					30.9		
	GS-IV			39.8					39.8					39.8		
	GP	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**
±Ro (mm)	**GS-I**	47.7	44.0	36.6	31.0	25.4	-47.7	-44.0	-36.6	-31.0	-25.4	-47.7	-44.0	-36.6	-31.0	-25.4
	GS-II	27.0	24.9	20.7	17.5	14.4	-27.0	-24.9	-20.7	-17.5	-14.4	-27.0	-24.9	-20.7	-17.5	-14.4
	GS-III	12.9	11.9	9.9	8.4	6.9	-12.9	-11.9	-9.9	-8.4	-6.9	-12.9	-11.9	-9.9	-8.4	-6.9
	GS-IV	16.6	15.3	12.8	10.8	8.9	-16.6	-15.3	-12.8	-10.8	-8.9	-16.6	-15.3	-12.8	-10.8	-8.9
	GP	**104.2**	**96.1**	**80.0**	**67.7**	**55.5**	**-104.2**	**-96.1**	**-80.0**	**-67.7**	**-55.5**	**-104.2**	**-96.1**	**-80.0**	**-67.7**	**-55.5**
RCI (mm)	**GS-I**	0.43	0.43	0.43	0.43	0.43	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.22
	GS-II	2.31	2.31	2.31	2.31	2.31	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16	1.16
	GS-III	1.80	1.80	1.80	1.80	1.80	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
	GS-IV	1.30	1.30	1.30	1.30	1.30	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
	GP	**5.84**	**5.84**	**5.84**	**5.84**	**5.84**	**2.92**	**2.92**	**2.92**	**2.92**	**2.92**	**2.92**	**2.92**	**2.92**	**2.92**	**2.92**
ΔS (mm)	**GS-I**	-10.6	-14.6	-28.0	5.7	7.6	-33.3	-46.1	-42.7	-23.9	-20.7	-42.8	-30.9	-26.9	-35.5	-26.1
	GS-II	-22.0	-56.4	-57.4	6.3	6.0	15.3	20.4	33.1	22.1	27.9	22.2	41.5	38.7	21.6	43.2
	GS-III	-6.0	14.8	0.0	15.4	-3.1	58.1	3.8	-50.8	-23.9	44.6	78.7	-22.1	28.4	-14.9	39.8
	GS-IV	-30.0	-4.8	-9.0	13.9	-40.7	-5.8	-10.0	-9.2	-16.7	12.6	-40.6	-19.6	1.4	1.4	10.2
	GP	**-68.6**	**-60.8**	**-94.4**	**41.3**	**-30.2**	**34.2**	**-32.0**	**-69.6**	**-42.4**	**64.4**	**17.5**	**-31.1**	**41.7**	**-27.4**	**67.1**
D		**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
ET Resd. (mm)	**GS-I**	151.2	143.5	122.7	150.7	147.0	76.5	71.8	59.9	59.5	68.2	76.5	71.8	59.9	49.7	62.8
	GS-II	67.3	30.8	25.6	86.1	82.7	51.8	59.0	75.8	68.0	76.9	58.7	80.1	81.5	67.5	92.2
	GS-III	36.0	55.8	39.0	52.9	32.9	75.2	34.9	29.1	24.2	67.7	95.8	34.9	48.5	24.2	62.9
	GS-IV	25.1	49.1	42.2	63.2	12.5	21.6	20.3	17.2	14.0	42.9	21.6	20.3	27.8	29.7	40.5
	GP	**279.6**	**279.2**	**229.6**	**352.9**	**275.1**	**225.1**	**185.9**	**182.1**	**165.7**	**255.8**	**252.7**	**207.1**	**217.7**	**171.1**	**258.5**
Es (mm)	**GS-I**	44.2	44.2	44.2	44.2	44.2	76.51	71.77	59.94	49.69	36.28	76.51	71.77	59.94	49.69	36.28
	GS-II	14.5	14.5	14.5	14.5	14.5	25.10	23.55	19.67	16.30	11.90	25.10	23.55	19.67	16.30	11.90
	GS-III	21.5	21.5	21.5	21.5	21.5	37.20	34.90	29.15	24.16	17.64	37.20	34.90	29.15	24.16	17.64
	GS-IV	12.5	12.5	12.5	12.5	12.5	21.63	20.29	16.94	14.05	10.26	21.63	20.29	16.94	14.05	10.26
	GP	**92.6**	**92.6**	**92.6**	**92.6**	**92.6**	**160.4**	**150.5**	**125.7**	**104.2**	**76.08**	**160.4**	**150.5**	**125.7**	**104.2**	**76.0**
Ev Resd. (mm)	**GS-I**	107.0	99.4	78.5	106.5	102.9	0.0	0.0	0.0	9.8	31.9	0.0	0.0	0.0	0.0	26.5
	GS-II	52.8	16.3	11.1	71.6	68.2	26.7	35.4	56.2	51.7	65.0	33.6	56.5	61.8	51.2	80.3
	GS-III	14.5	34.4	17.5	31.4	11.4	38.0	0.0	0.0	0.0	50.1	58.6	0.0	19.4	0.0	45.3
	GS-IV	12.6	36.6	29.8	50.7	0.0	0.0	0.0	0.2	0.0	32.7	0.0	0.0	10.9	15.7	30.3
	GP	**187.0**	**186.6**	**136.9**	**260.3**	**182.5**	**64.7**	**35.4**	**56.4**	**61.5**	**179.7**	**92.2**	**56.5**	**92.0**	**66.9**	**182.4**

NB. P = cropping season rainfall, ±Ro = Run-on/Runoff, RCI = rainfall canopy interception, Δ S= change in soil water content, D = drainage, ET = Resd. Evapotranspiration calculated as residual, Es = soil water evaporation and Ev Resd. = transpiration calculated as residual of ET. All components are computed in mm.

Appendix 7.5 RSL-3 treatment **w**ater balance components sheet for cropping season 2008/09 for different growth stages under different mulch level treatments (ML) for Kenilworth Bainsvlei ecotope.

RSL-3		BA					RA1					RA2					RA3				
ML		0%	12%	39%	64%	96%	0%	12%	39%	64%	96%	0%	12%	39%	64%	96%	0%	12%	39%	64%	96%
P (mm)	GS-I			114.5					114.5					114.5					114.5		
	GS-II			64.6					64.6					64.6					64.6		
	GS-III			30.9					30.9					30.9					30.9		
	GS-IV			39.8					39.8					39.8					39.8		
	GP	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**	**249.8**
±Ro (mm)	GS-I	34.8	31.7	25.8	21.9	19.0	-34.8	-31.7	-25.8	-21.9	-19.0	-34.8	-31.7	-25.8	-21.9	-19.0	-34.8	-31.7	-25.8	-21.9	-19.0
	GS-II	19.7	17.9	14.6	12.4	10.7	-19.7	-17.9	-14.6	-12.4	-10.7	-19.7	-17.9	-14.6	-12.4	-10.7	-19.7	-17.9	-14.6	-12.4	-10.7
	GS-III	9.4	8.6	7.0	5.9	5.1	-9.4	-8.6	-7.0	-5.9	-5.1	-9.4	-8.6	-7.0	-5.9	-5.1	-9.4	-8.6	-7.0	-5.9	-5.1
	GS-IV	12.1	11.0	9.0	7.6	6.6	-12.1	-11.0	-9.0	-7.6	-6.6	-12.1	-11.0	-9.0	-7.6	-6.6	-12.1	-11.0	-9.0	-7.6	-6.6
	GP	**76.0**	**69.2**	**56.4**	**47.9**	**41.5**	**-76.0**	**-69.2**	**-56.4**	**-47.9**	**-41.5**	**-76.0**	**-69.2**	**-56.4**	**-47.9**	**-41.5**	**-76.0**	**-69.2**	**-56.4**	**-47.9**	**-41.5**
RCI (mm)	GS-I	0.50	0.50	0.50	0.50	0.50	0.25	0.25	0.25	0.25	0.25						0.25	0.25	0.25	0.25	0.25
	GS-II	2.92	2.92	2.92	2.92	2.92	1.46	1.46	1.46	1.46	1.46						1.46	1.46	1.46	1.46	1.46
	GS-III	2.49	2.49	2.49	2.49	2.49	1.25	1.25	1.25	1.25	1.25						1.25	1.25	1.25	1.25	1.25
	GS-IV	1.79	1.79	1.79	1.79	1.79	0.90	0.90	0.90	0.90	0.90						0.90	0.90	0.90	0.90	0.90
	GP	**7.70**	**7.70**	**7.70**	**7.70**	**7.70**	**3.85**	**3.85**	**3.85**	**3.85**	**3.85**						**3.85**	**3.85**	**3.85**	**3.85**	**3.85**
ΔS (mm)	GS-I	-35.1	-44.5	-4.1	5.2	1.0	-64.7	-41.1	-9.1	-20.9	-13.7	-5.4	-19.8	17.1	-22.4	-5.2	-21.4	-4.7	-30.6	-17.7	-6.8
	GS-II	-22.0	-27.5	-29.5	-15.8	98.4	8.6	38.6	1.6	21.8	16.4	0.3	20.9	-21.5	37.2	11.0	36.1	37.3	15.5	45.5	25.4
	GS-III	-6.0	7.0	22.3	4.5	26.3	66.5	31.1	47.1	9.2	46.7	66.7	30.8	53.2	-27.1	20.1	82.8	45.4	51.1	-16.8	35.1
	GS-IV	-30.0	32.3	98.8	27.2	-0.4	7.8	4.3	9.1	-8.6	-5.3	0.2	10.3	5.9	-9.0	6.6	3.3	0.6	25.9	-10.6	-0.1
	GP	**-93.1**	**-32.7**	**87.4**	**21.1**	**125.3**	**18.2**	**32.9**	**48.7**	**1.6**	**44.1**	**61.8**	**42.2**	**54.8**	**-21.2**	**32.5**	**100.8**	**78.6**	**61.9**	**0.4**	**53.5**
D		**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
ET Resd. (mm)	GS-I	113.7	101.1	135.7	141.1	133.9	76.5	71.8	79.4	71.5	81.6	78.9	74.1	105.8	70.2	90.3	76.5	77.9	59.9	74.6	88.5
	GS-II	59.4	52.1	46.8	58.3	170.9	52.0	83.8	50.1	72.6	68.8	45.2	67.6	28.4	89.4	64.9	79.5	82.5	64.0	96.2	77.8
	GS-III	31.8	44.0	57.7	38.8	59.8	86.7	52.1	69.7	33.0	71.2	88.2	53.2	77.1	25.3	45.8	103.1	66.5	73.8	24.2	59.6
	GS-IV	20.1	81.4	145.8	72.8	44.2	34.6	32.2	39.0	22.6	27.0	27.8	39.0	36.7	23.2	39.8	30.0	28.4	55.8	20.6	32.1
	GP	**225.0**	**278.6**	**386.0**	**311.1**	**408.8**	**249.9**	**239.9**	**238.2**	**199.7**	**248.6**	**240.1**	**233.9**	**248.1**	**208.1**	**240.9**	**289.2**	**255.4**	**253.6**	**215.7**	**258.0**
Es (mm)	GS-I	26.0	26.0	26.0	26.0	26.0	76.5	71.8	59.9	49.7	36.3	78.87	74.14	62.31	52.06	38.65	76.5	71.8	59.9	49.7	36.3
	GS-II	8.5	8.5	8.5	8.5	8.5	25.1	23.6	19.7	16.3	11.9	25.88	24.33	20.44	17.08	12.68	25.1	23.6	19.7	16.3	11.9
	GS-III	12.7	12.7	12.7	12.7	12.7	37.2	34.9	29.1	24.2	17.6	38.35	36.05	30.30	25.31	18.79	37.2	34.9	29.1	24.2	17.6
	GS-IV	7.4	7.4	7.4	7.4	7.4	21.6	20.3	16.9	14.0	10.3	22.29	20.96	17.61	14.71	10.92	21.6	20.3	16.9	14.0	10.3
	GP	**54.6**	**54.6**	**54.6**	**54.6**	**54.6**	**160.4**	**150.5**	**125.7**	**104.2**	**76.1**	**165.4**	**155.5**	**130.7**	**109.2**	**81.0**	**160.4**	**150.5**	**125.7**	**104.2**	**76.1**
Ev Resd. (mm)	GS-I	87.7	75.1	109.6	115.1	107.9	0.0	0.0	19.4	21.8	45.3	0.0	0.0	43.5	18.2	51.7	0.0	6.1	0.0	24.9	52.2
	GS-II	50.8	43.6	38.3	49.8	162.3	26.9	60.2	30.5	56.3	56.9	19.4	43.2	8.0	72.4	52.2	54.4	59.0	44.4	79.9	65.8
	GS-III	19.2	31.3	45.0	26.2	47.2	49.5	17.2	40.6	8.8	53.5	49.8	17.1	46.8	0.0	27.0	65.9	31.6	44.6	0.0	42.0
	GS-IV	12.8	74.0	138.4	65.5	36.9	13.0	11.9	22.1	8.6	16.7	5.5	18.1	19.1	8.4	28.9	8.4	8.2	38.9	6.6	21.9
	GP	**170.5**	**224.0**	**331.4**	**256.5**	**354.3**	**89.5**	**89.4**	**112.5**	**95.5**	**172.5**	**74.7**	**78.4**	**117.5**	**99.0**	**159.8**	**128.7**	**104.9**	**127.8**	**111.5**	**181.9**

NB. P = cropping season rainfall, ±Ro = Run-on/Runoff, RCI = rainfall canopy interception, Δ S= change in soil water content, D = drainage, ET = Resd. Evapotranspiration calculated as residual, Es = soil water evaporation and Ev Resd. = transpiration calculated as residual of ET. All components are computed in mm.

Appendix 8.1 Hourly measured micrometeorological variables in a wide and narrow runoff strip lengths for the period of 06 Feb, 2009 a) water vapour pressure b) virtual potential temperatures.

a) Hourly water vapour pressure values (ea) (KPa) measured at different profile heights in wide and narrow runoff lengths as presented in Fig.8.4 and 8.5, partially reproduced for a given period (06 Feb., 2009).

Profile, z (m)	Runoff length (RSL)	Morning (hrs)			Midday (hrs)			Afternoon (hrs)			Evening (hrs)			Nighttime (hrs)		
		8:00	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**
0.30 (LP)	Wide	1.68	1.62	1.55	1.53	1.45	1.43	1.39	1.32	1.32	1.21	1.14	1.16	1.28	1.32	1.38
	Narrow	1.60	1.53	1.46	1.44	1.37	1.38	1.31	1.26	1.26	1.13	1.07	1.12	1.23	1.26	1.32
0.60 (ML)	Wide	1.64	1.59	1.52	1.51	1.43	1.40	1.36	1.30	1.30	1.19	1.12	1.14	1.27	1.30	1.36
	Narrow	1.65	1.57	1.49	1.49	1.41	1.39	1.34	1.29	1.29	1.17	1.10	1.15	1.27	1.29	1.36
0.90 (MU)	Wide	1.61	1.56	1.49	1.47	1.40	1.36	1.33	1.26	1.26	1.15	1.09	1.11	1.23	1.26	1.33
	Narrow	1.60	1.52	1.46	1.45	1.39	1.37	1.32	1.25	1.25	1.16	1.09	1.12	1.23	1.25	1.32
1.20 (UP)	Wide	1.65	1.59	1.52	1.50	1.44	1.39	1.35	1.30	1.30	1.17	1.12	1.13	1.26	1.30	1.37
	Narrow	1.59	1.51	1.43	1.42	1.35	1.32	1.27	1.25	1.25	1.11	1.04	1.07	1.21	1.25	1.32

b) Hourly virtual potential temperatures; θv (K) measured at different profile heights in wide and narrow runoff lengths as presented in Fig.8.4 and 8.5, partially reproduced for 06 Feb, 2009.

Profile, z (m)	Runoff length (RSL)	Morning (hrs)			Midday (hrs)			Afternoon (hrs)			Evening (hrs)			Nighttime (hrs)		
		8:00	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**
0.30 (LP)	Wide	309.8	312.4	315.0	316.8	318.5	320.0	320.8	322.1	323.2	323.3	321.8	318.7	313.9	311.8	311.4
	Narrow	309.0	311.8	314.0	315.9	317.6	319.4	320.3	322.0	322.6	323.0	320.4	317.5	313.0	311.0	310.7
0.60 (ML)	Wide	309.3	311.7	314.2	315.8	317.2	318.5	319.4	320.2	321.6	321.7	320.0	317.9	313.3	311.1	310.8
	Narrow	309.4	312.0	314.1	316.1	317.5	319.2	319.9	321.4	321.8	322.1	320.4	317.9	313.3	311.3	311.0
0.90 (MU)	Wide	309.2	311.6	314.0	315.5	316.9	318.1	319.2	320.2	321.2	321.4	319.6	318.0	313.2	311.2	310.8
	Narrow	309.4	311.7	313.8	315.6	316.8	318.1	318.9	320.1	320.7	320.9	319.3	317.9	313.1	311.1	310.7
1.20 (UP)	Wide	309.2	311.6	313.8	315.3	316.9	318.2	319.0	319.9	320.9	321.1	319.9	318.2	313.4	311.3	311.0
	Narrow	309.2	311.4	313.4	315.1	316.4	317.8	318.3	319.3	320.0	320.3	318.8	317.9	313.0	311.0	310.6

Appendix 8.2 Hourly measured micrometeorological variables in a wide and narrow runoff strip lengths for the period of 21., Feb, 2009 a) water vapour pressure b) virtual potential temperatures.

a) Hourly water vapour pressure values, ea (KPa) measured at different profile heights in wide and narrow runoff lengths as presented in Fig. 8.6 and Fig. 8.7, partially reproduced for 21 Feb., 2009.

Profile, z(m)	Runoff length (RSL)	Morning (hrs)			Midday (hrs)			Afternoon (hrs)			Evening (hrs)			Nighttime (hrs)		
		8:00	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**
0.40 (LP)	Wide	2.00	2.02	2.20	2.25	2.25	2.21	319.0	2.16	2.10	1.95	1.91	2.10	2.18	2.12	2.12
	Narrow	1.92	1.95	2.12	2.20	2.11	2.11	318.4	2.01	1.97	1.78	1.77	2.03	2.10	2.05	2.04
0.80 (ML)	Wide	1.96	1.98	2.17	2.22	2.22	2.18	318.4	2.14	2.07	1.91	1.86	2.07	2.13	2.09	2.09
	Narrow	1.98	1.99	2.15	2.26	2.15	2.13	318.8	2.06	2.03	1.84	1.83	2.08	2.16	2.11	2.10
1.20 (MU)	Wide	1.93	1.95	2.11	2.17	2.15	2.13	318.4	2.04	2.03	1.86	1.81	2.02	2.07	2.04	2.04
	Narrow	1.96	1.97	2.13	2.21	2.12	2.09	318.3	1.99	2.00	1.80	1.78	2.03	2.11	2.07	2.07
1.60 (UP)	Wide	1.95	1.98	2.13	2.18	2.18	2.14	318.8	2.04	2.04	1.87	1.82	2.03	2.10	2.06	2.08
	Narrow	1.90	1.91	2.06	2.11	2.09	2.02	318.3	1.91	1.95	1.75	1.72	1.98	2.06	2.02	2.02

b) Hourly virtual potential temperatures, θv (K) measured at different profile heights in wide and narrow runoff lengths as presented in Fig. 8.6 and Fig. 8.7, partially reproduced 21 Feb., 2009.

Profile, z(m)	Runoff length (RSL)	Morning (hrs)			Midday (hrs)			Afternoon (hrs)			Evening (hrs)			Nighttime (hrs)		
		8:00	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**
0.40 (LP)	Wide	309.8	311.4	314.8	316.0	316.9	317.3	319.0	320.0	319.6	320.3	316.5	314.9	313.3	312.4	312.0
	Narrow	307.7	311.4	314.8	316.7	316.6	316.8	318.4	319.0	318.6	318.8	315.8	314.5	312.9	312.1	311.7
0.80 (ML)	Wide	309.6	311.3	314.9	316.1	317.0	317.1	318.4	319.5	319.1	319.6	316.3	314.9	313.0	312.3	311.8
	Narrow	310.1	311.8	315.5	317.2	317.1	317.3	318.8	319.4	319.1	319.1	316.2	314.8	313.3	312.5	312.0
1.20 (MU)	Wide	309.6	311.3	314.5	315.8	316.6	316.9	318.4	319.2	319.1	319.7	316.3	314.6	312.9	312.3	311.8
	Narrow	309.7	311.6	316.2	317.2	317.0	317.2	318.3	319.0	318.9	318.7	315.9	314.4	312.9	312.2	311.7
1.60 (UP)	Wide	309.8	311.6	315.3	316.3	317.2	317.3	318.8	319.5	319.4	319.9	316.5	314.8	313.1	312.5	312.1
	Narrow	309.5	311.4	316.2	317.2	317.1	317.1	318.3	318.7	318.7	318.8	315.7	314.2	312.6	311.9	311.5

Appendix 8.3 Hourly measured micrometeorological variables in a wide and narrow runoff strip lengths for the period of 11 Mar., 2009 a) water vapour pressure b) virtual potential temperatures.

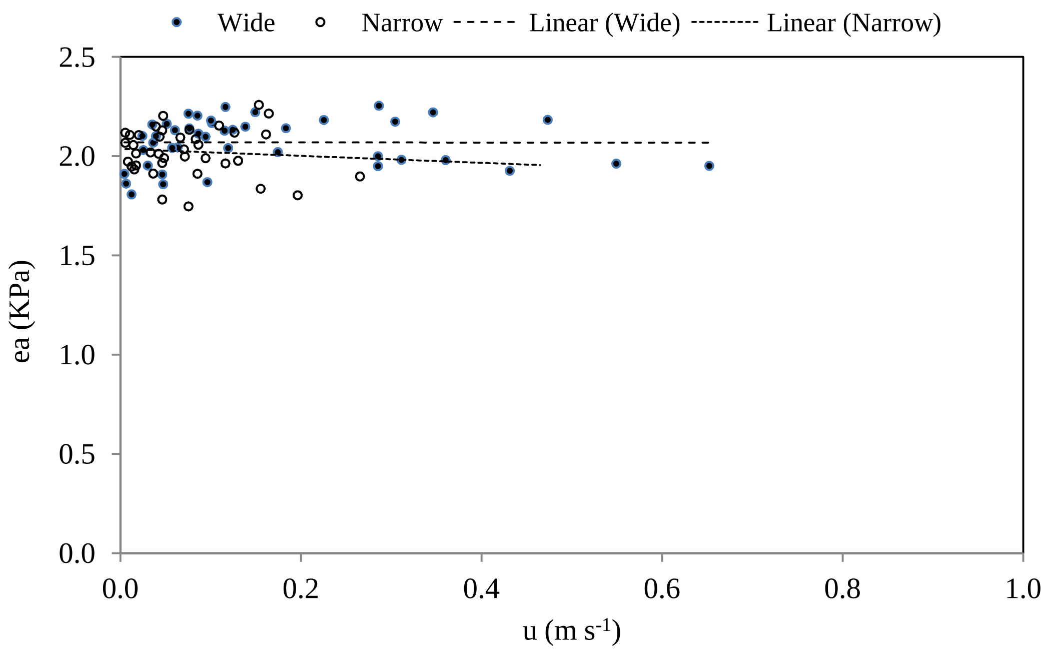
a) Hourly vapour pressure values, ea (KPa) measured at different profile heights in wide and narrow runoff lengths as presented in Fig.8.9 partially reproduced (11 Mar., 2009).

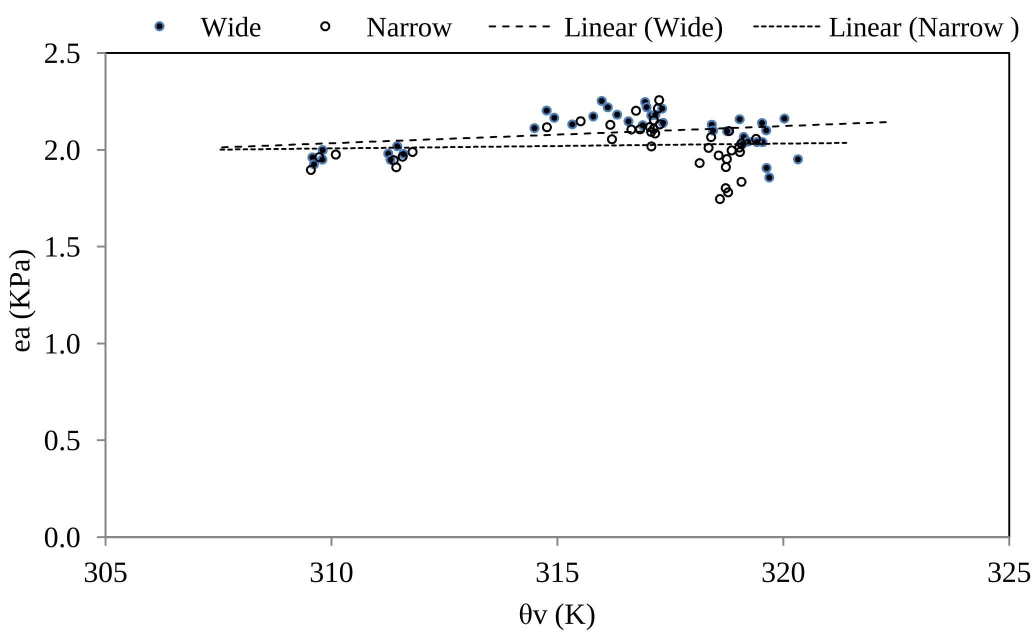
Profile, z(m)	Runoff length (RSL)	Morning (hrs)			Midday (hrs)			Afternoon (hrs)			Evening (hrs)			Nighttime (hrs)		
		8:00	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**
0.55 (LP)	Wide	1.73	1.84	1.85	1.86	1.76	1.63	1.51	1.41	1.38	1.46	1.49	1.42	1.48	1.59	1.62
	Narrow	1.70	1.80	1.76	1.69	1.65	1.54	1.42	1.37	1.34	1.39	1.41	1.35	1.41	1.53	1.55
1.10 (ML)	Wide	1.71	1.82	1.82	1.82	1.69	1.58	1.47	1.37	1.33	1.42	1.45	1.38	1.44	1.57	1.59
	Narrow	1.74	1.85	1.84	1.80	1.71	1.60	1.47	1.41	1.25	1.44	1.46	1.39	1.46	1.57	1.60
1.65 (MU)	Wide	1.67	1.77	1.78	1.77	1.67	1.57	1.44	1.34	1.32	1.39	1.42	1.35	1.42	1.54	1.56
	Narrow	1.75	1.81	1.80	1.78	1.69	1.55	1.44	1.40	1.23	1.41	1.43	1.35	1.43	1.54	1.57
2.20 (UP)	Wide	1.68	1.77	1.77	1.80	1.67	1.56	1.42	1.33	1.32	1.41	1.43	1.35	1.43	1.55	1.57
	Narrow	1.67	1.74	1.75	1.71	1.64	1.48	1.36	1.30	1.08	1.38	1.39	1.32	1.39	1.51	1.54

a) Hourly virtual potential temperatures, θv (K) measured at different profile heights in wide and narrow runoff lengths as presented in Fig. 8.9 (11 Mar., 2009).

Profile, z(m)	Runoff length (RSL)	Morning (hrs)			Midday (hrs)			Afternoon (hrs)			Evening (hrs)			Nighttime (hrs)		
		8:00	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**	**18:00**	**19:00**	**20:00**	**21:00**	**22:00**
0.55 (LP)	Wide	306.4	310.8	314.0	316.8	317.8	318.5	318.6	321.1	320.2	313.5	311.8	310.9	309.9	308.8	308.4
	Narrow	307.2	312.0	318.8	320.6	319.2	318.9	318.7	320.2	319.8	312.8	311.3	310.5	309.5	308.4	308.0
1.10 (ML)	Wide	306.9	311.4	314.2	316.8	317.3	318.0	318.3	320.3	319.8	314.4	311.8	311.1	310.1	309.0	308.6
	Narrow	308.0	313.6	316.9	318.4	318.5	319.3	318,8	319.9	316.0	313.4	311.6	310.8	309.8	308.6	308.3
1.65 (MU)	Wide	306.6	310.2	312.6	315.1	315.9	316.8	317.2	318.6	318.4	312.2	311.1	310.6	309.8	308.4	308.1
	Narrow	306.9	310.6	314.3	316.8	317.6	317.1	317.2	318.6	314.9	312.5	311.1	310.5	309.4	308.3	308.0
2.20 (UP)	Wide	307.0	310.3	312.5	315.9	316.1	316.4	316.8	317.9	317.8	312.3	311.2	310.8	309.7	308.6	308.2
	Narrow	308.0	311.3	313.6	315.6	317.0	315.9	316.2	317.3	314.1	312.1	310.9	310.4	309.3	308.2	307.9

Appendix 8.4 Daytime relationship a) for wind speed (u) versus water vapour (ea) and b) for virtual potential temperature (θv) versus ea of all profile measurements (n=40) on 6 Feb., 2009 (62 DAP) on wide and narrow runoff strips.





Appendix 9.1 Mean comparison of three hours ea, θv and u variables during morning, daytime, evening and nighttime for wide RSL

DOY		107					108					112					117				
Z (m)		Morning	Daytime	Evening	Night	*mean*	Morning	Daytime	Evening	Night	*mean*	Morning	Daytime	Evening	Night	*mean*	Morning	Daytime	Evening	Night	*mean*
ea (KPa)	1.8	0.77	0.73	0.74	0.76	**0.75a**	0.90	0.79	0.80	0.83	**0.83a**	1.06	1.08	1.06	1.11	**1.08a**	0.88	0.76	0.82	0.86	**0.83a**
	2.1	0.76	0.72	0.73	0.75	**0.74ab**	0.89	0.78	0.79	0.82	**0.82ab**	1.06	1.06	1.05	1.10	**1.07ab**	0.88	0.76	0.81	0.85	**0.82ab**
	2.4	0.74	0.71	0.71	0.73	**0.72ab**	0.87	0.77	0.77	0.81	**0.81bc**	1.04	1.04	1.03	1.08	**1.04d**	0.86	0.74	0.79	0.83	**0.80ab**
	2.7	0.74	0.71	0.71	0.74	**0.73bc**	0.87	0.77	0.78	0.81	**0.81ac**	1.04	1.05	1.03	1.08	**1.05dc**	0.86	0.74	0.79	0.84	**0.81a-c**
	3.0	0.72	0.68	0.69	0.72	**0.70bc**	0.85	0.74	0.76	0.79	**0.79dc**	1.02	1.02	1.01	1.06	**1.03e**	0.84	0.72	0.77	0.82	**0.79bc**
	3.3	0.75	0.71	0.72	0.73	**0.73ab**	0.89	0.78	0.78	0.82	**0.82ab**	1.05	1.05	1.05	1.10	**1.06bc**	0.87	0.75	0.79	0.85	**0.81ab**
	3.9	0.75	0.72	0.71	0.72	**0.72ab**	0.89	0.78	0.78	0.80	**0.81ab**	1.05	1.05	1.03	1.08	**1.05dc**	0.87	0.75	0.77	0.84	**0.81ab**
	4.5	0.71	0.67	0.67	0.69	**0.68c**	0.84	0.73	0.74	0.76	**0.77d**	1.01	1.01	1.01	1.06	**1.02e**	0.82	0.70	0.74	0.82	**0.77c**
mean		**0.74a**	**0.70d**	**0.71c**	**0.73b**		**0.88a**	**0.77c**	**0.78c**	**0.81b**		**1.04b**	**1.04b**	**1.03c**	**1.08a**		**0.86a**	**0.74c**	**0.78b**	**0.84a**	
LSD		**Per= 0.026 Height= 0.036**					**Per= 0.017 z= 0.024**					**Per= 0.008 z= 0.011**					**Per= 0.027 z= 0.038**				
θv (K)	1.8	305.9	315.7	308.2	303.6	**308.3**	305.8	314.4	309.4	300.7	**307.6**	301.4	308.5	306.8	304.3	**305.2**	300.8	309.1	302.5	296.4	**302.2**
	2.1	306.4	316.1	308.7	304.0	**308.8**	306.6	314.8	309.8	301.1	**308.1**	301.7	308.9	307.2	304.7	**305.6**	302.2	309.4	303.0	296.8	**302.9**
	2.4	305.7	315.2	308.4	303.7	**308.2**	305.9	314.0	309.5	300.8	**307.5**	301.2	308.1	306.8	304.2	**305.1**	301.2	308.4	302.7	296.5	**302.2**
	2.7	305.8	315.3	308.7	304.0	**308.5**	306.0	314.1	309.8	301.1	**307.7**	301.3	308.3	307.0	304.4	**305.2**	301.4	308.6	303.0	296.8	**302.4**
	3.0	306.1	315.2	308.4	303.9	**308.4**	306.6	314.0	309.5	300.9	**307.8**	301.2	308.0	306.7	304.2	**305.0**	302.9	308.8	302.8	296.4	**302.7**
	3.3	308.5	317.7	308.2	303.4	**309.4**	309.3	315.9	309.7	301.1	**309.0**	302.0	309.5	306.9	304.4	**305.7**	306.3	312.3	302.7	296.5	**304.4**
	3.9	307.3	316.3	308.5	303.7	**309.0**	308.4	314.8	309.7	301.8	**308.7**	301.6	308.6	306.7	304.2	**305.3**	305.0	311.4	302.9	296.6	**304.0**
	4.5	305.3	314.4	309.2	304.1	**308.2**	305.6	313.3	310.0	303.0	**308.0**	300.9	307.4	306.7	304.2	**304.8**	301.2	307.7	303.5	297.1	**302.4**
mean		**306.4c**	**315.7a**	**308.6b**	**303.8d**		**306.8c**	**314.4a**	**309.7b**	**301.3d**		**301.4d**	**308.4a**	**306.8b**	**304.3c**		**302.6b**	**309.5a**	**302.9b**	**296.6d**	
LSD		**Per= 1.77 z= ns**					**Per= 1.419 z= ns**					**Per= 0.926 z= ns**					**Per= 1.677 z= ns**				
u ($m\ s^{-1}$)	1.8	0.70	0.60	0.01	0.07	**0.35e**	0.18	1.25	0.02	0.00	**0.36d**	2.88	3.08	1.11	2.01	**2.27g**	0.14	0.40	0.07	0.00	**0.15d**
	2.1	1.04	0.95	0.03	0.23	**0.56ed**	0.49	1.74	0.06	0.00	**0.57cd**	3.31	3.56	1.58	2.46	**2.73fg**	0.26	0.56	0.14	0.04	**0.25dc**
	2.4	1.44	1.20	0.12	0.37	**0.78dc**	0.69	2.13	0.14	0.10	**0.76cb**	3.68	3.95	1.85	2.77	**3.06fe**	0.55	0.73	0.23	0.29	**0.45c**
	2.7	1.52	1.36	0.17	0.41	**0.87bc**	0.76	2.40	0.15	0.06	**0.84b**	3.94	4.30	2.05	3.01	**3.33de**	0.61	0.82	0.30	0.45	**0.54c**
	3.0	1.71	1.47	0.29	0.56	**1.01dc**	0.79	2.53	0.17	0.00	**0.87b**	4.22	4.59	2.19	3.24	**3.56dc**	0.68	0.81	0.36	0.59	**0.61bc**
	3.3	1.89	1.59	0.42	0.70	**1.15ab**	0.99	2.78	0.28	0.37	**1.11a**	4.53	4.93	2.44	3.49	**3.85bc**	0.81	0.94	0.50	0.89	**0.78b**
	3.9	2.01	1.76	0.50	0.84	**1.28a**	1.13	3.05	0.30	0.61	**1.27a**	4.92	5.38	2.67	3.80	**4.19ba**	0.94	1.02	0.59	1.32	**0.97ab**
	4.5	1.92	1.85	0.43	0.83	**1.25a**	1.16	3.24	0.39	0.32	**1.28a**	5.27	5.80	2.93	4.15	**4.53a**	0.91	1.04	0.63	1.54	**1.03a**
mean		**1.53a**	**1.35a**	**0.25c**	**0.50b**		**0.77b**	**2.39a**	**0.19c**	**0.18c**		**4.09b**	**4.45a**	**2.10d**	**3.12c**		**0.61b**	**0.79a**	**0.35c**	**0.63b**	
LSD		**Per= 0.206 z= 0.290**					**Per= 0.156 z= 0.220**					**Per= 0.335 z= 0.474**					**Per= 0.150 z= 0.212**				

DOY= day of the year, LSD= least significant difference, z= height from ground and Per= periods represent: morning, daytime, evening, and nighttime

Appendix 9.2 Mean comparison of three hours ea, θv and u variables during morning, daytime, evening and nighttime for narrow RSL

DOY		125					126					127					131				
z (m)		Morning	Daytime	Evening	Night	***mean***	Morning	Daytime	Evening	Night	***mean***	Morning	Daytime	Evening	Night	***mean***	Morning	Daytime	Evening	Night	***mean***
ea (KPa)	**1.8**	1.36	1.37	1.33	1.31	**1.34a**	1.26	1.41	1.43	1.19	**1.32a**	1.22	0.96	0.87	0.83	**0.97**	0.94	0.89	0.85	0.83	**0.88**
	2.1	1.36	1.36	1.33	1.31	**1.34a**	1.26	1.39	1.43	1.19	**1.32a**	1.22	0.95	0.86	0.83	**0.96**	0.94	0.87	0.85	0.83	**0.87**
	2.4	1.32	1.32	1.29	1.28	**1.30a-c**	1.22	1.36	1.39	1.16	**1.29ab**	1.19	0.93	0.83	0.80	**0.94**	0.91	0.86	0.83	0.81	**0.85**
	2.7	1.33	1.32	1.30	1.29	**1.31a-c**	1.23	1.36	1.40	1.17	**1.29ab**	1.19	0.92	0.83	0.79	**0.94**	0.92	0.86	0.83	0.82	**0.86**
	3.0	1.31	1.29	1.27	1.26	**1.28bc**	1.21	1.32	1.37	1.15	**1.26b**	1.17	0.89	0.81	0.77	**0.91**	0.90	0.83	0.81	0.80	**0.84**
	3.3	1.34	1.33	1.31	1.30	**1.32ab**	1.24	1.34	1.41	1.19	**1.30ab**	1.22	0.94	0.83	0.79	**0.94**	0.93	0.86	0.84	0.83	**0.86**
	3.9	1.34	1.32	1.31	1.33	**1.33ab**	1.26	1.33	1.41	1.26	**1.31a**	1.28	0.94	0.81	0.77	**0.95**	0.93	0.87	0.83	0.84	**0.87**
	4.5	1.28	1.25	1.26	1.25	**1.26c**	1.18	1.27	1.36	1.23	**1.26b**	1.22	0.88	0.77	0.73	**0.90**	0.88	0.82	0.82	0.82	**0.83**
mean		**1.33a**	**1.32ab**	**1.30ab**	**1.29b**		**1.23c**	**1.35b**	**1.40a**	**1.19d**		**1.21a**	**0.93b**	**0.83c**	**0.79c**		**0.92a**	**0.86b**	**0.83b**	**0.82b**	
LSD		**Per= 0.034**		**z= 0.048**			**Per= 0.0313**		**z= 0.044**			**Per= 0.063**		**z= ns**			**Per= 0.040**		**z= ns**		
θv (K)	**1.8**	302.3	307.0	302.2	300.5	**303.0**	301.2	309.8	305.3	298.9	**303.8**	301.4	309.3	301.5	297.6	**302.5**	300.0	308.5	301.4	297.9	**302.0**
	2.1	302.7	307.5	302.7	300.9	**303.4**	301.8	309.9	305.8	299.4	**304.2**	302.4	309.7	302.2	298.2	**303.1**	300.6	309.0	301.8	298.3	**302.4**
	2.4	302.2	306.8	302.2	300.5	**302.9**	301.2	309.1	305.4	299.1	**303.7**	301.7	308.9	302.1	297.9	**302.6**	300.0	308.2	301.5	298.2	**302.0**
	2.7	302.4	306.9	302.4	300.6	**303.1**	301.3	309.2	305.6	299.4	**303.9**	302.0	309.0	302.5	298.3	**302.9**	300.1	308.4	301.8	298.5	**302.2**
	3.0	302.2	307.0	302.1	300.3	**302.9**	301.4	309.3	305.4	299.2	**303.8**	302.4	309.1	302.3	298.1	**303.0**	300.2	308.3	301.6	298.2	**302.1**
	3.3	302.4	307.3	302.3	300.6	**303.2**	301.9	309.3	305.7	299.6	**304.1**	303.1	309.4	302.7	298.6	**303.4**	300.6	308.5	301.9	298.6	**302.4**
	3.9	302.3	307.7	301.7	300.2	**303.0**	302.2	310.6	305.6	300.3	**304.7**	304.8	311.4	302.5	298.4	**304.3**	301.0	309.7	301.9	299.1	**302.9**
	4.5	302.0	306.3	302.1	300.4	**302.7**	300.9	308.3	305.6	301.1	**304.0**	302.1	308.1	302.9	299.0	**303.0**	299.6	307.6	302.4	299.5	**302.3**
mean		**302.3b**	**307.1a**	**302.2b**	**300.5c**		**301.5c**	**309.4a**	**305.5b**	**299.6d**		**302.5b**	**309.4a**	**302.4b**	**298d**		**300.3b**	**308.5a**	**301.8b**	**298.5c**	
LSD		**Per= 0.560**		**z= ns**			**Per= 1.167**		**z= ns**			**Per= 1.563**		**z= ns**			**Per= 1.69**		**z= ns**		
u ($m\ s^{-1}$)	**1.8**	1.00	2.05	0.86	0.17	**1.02d**	0.40	1.17	0.08	0.00	**0.41d**	0.06	0.93	0.04	0.32	**0.34d**	0.56	1.55	0.05	0.06	**0.55d**
	2.1	1.29	2.53	1.18	0.43	**1.36d**	0.67	1.38	0.29	0.00	**0.59d**	0.08	1.20	0.09	0.58	**0.49d**	0.74	1.80	0.13	0.26	**0.73cd**
	2.4	2.02	3.37	1.65	0.73	**1.94c**	1.07	1.75	0.53	0.03	**0.84c**	0.18	1.55	0.17	0.82	**0.68b-d**	1.27	2.13	0.29	0.61	**1.07b**
	2.7	2.31	4.02	1.82	0.84	**2.25cb**	1.13	1.88	0.56	0.00	**0.89c**	0.17	1.73	0.19	0.92	**0.75b-d**	1.34	2.29	0.42	0.72	**1.19b**
	3.0	2.56	4.36	2.01	1.00	**2.48d**	1.37	2.04	0.71	0.06	**1.03c**	0.16	1.76	0.24	1.02	**0.79a-d**	1.42	2.41	0.55	0.82	**1.30b**
	3.3	2.81	4.69	2.20	1.16	**2.71ab**	1.62	2.19	0.91	0.27	**1.24b**	0.34	1.98	0.34	1.18	**0.96a-c**	1.78	2.61	0.69	1.21	**1.57ab**
	3.9	3.10	5.51	2.35	1.34	**3.07a**	1.85	2.30	1.03	0.25	**1.36ab**	0.29	2.14	0.31	1.34	**1.02ab**	1.90	2.82	0.75	1.51	**1.74a**
	4.5	2.96	5.28	2.34	1.45	**3.01a**	1.97	2.32	1.27	0.46	**1.50a**	0.35	2.29	0.46	1.49	**1.15a**	1.59	3.02	0.93	1.75	**1.82a**
mean		**2.26b**	**3.98a**	**1.80b**	**0.89c**		**1.26b**	**1.88a**	**0.67c**	**0.13d**		**0.20c**	**1.70a**	**0.23c**	**0.96b**		**1.33b**	**2.33a**	**0.47d**	**0.87c**	
LSD		**Per= 0.397**		**z= 0.561**			**Per= 0.144**		**z= 0.204**			**Per= 0.323**		**z= 0.457**			**Per= 0.198**		**z= 0.281**		

DOY= day of the year, LSD= least significant difference, z= height from ground and Per= periods represent: morning, daytime, evening, and nighttime