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MODELLING THE TEMPORAL AND SPATIAL VARIATION OF
EVAPOTRANSPIRATION FROM IRRIGATED PASTURES IN
CANTERBURY

A thesis submitted for a degree of
Doctor of Philosophy

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by
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Modelling the temporal and spatial variation of evapotranspiration from irrigated pastures in Canterbury

by

Jenna Van Housen

Evapotranspiration is a critical factor for local and regional planning, in terms of both water quality and quantity, to inform decisions around water catchment management, irrigation, water storage, and resource sustainability. Despite its importance, understanding of evapotranspiration from irrigated dairy pasture in Canterbury has to date been relatively limited. The focus of this research was, therefore, to improve understanding of evapotranspiration from ryegrass-based irrigated pastures under grazing. This was achieved through quantifying relationships between actual evapotranspiration and canopy development and evaluation and validation of methods commonly applied in the estimation of potential canopy evapotranspiration (PETc) for grazed perennial ryegrass (Lolium perenne L.) pasture.

A network of nine lysimeters located at three sites across the mid to north Canterbury Plains was used. Pasture canopy measurements were taken throughout the study at one of the sites, and the biophysical model 'DairyMod' used to simulate pasture growth at all three sites. The 'DairyMod' and 'HYDRUS-1D' models were used to simulate soil water flow, and used to support lysimeter-based estimates of actual evapotranspiration. Methods examined for modelling PETc included the use of a crop coefficient time series and a number of commonly applied single-layer models including Penman-Monteith (PM), FAO-modified Penman-Monteith (PM_{FAO}) and Priestley-Taylor (PT), and the dual-layer dual crop coefficient (DCC) and Shuttleworth-Wallace (SWW) models. ‘DairyMod’ and ‘HYDRUS’ and selected PETc models were validated with data collected under a controlled, perennial ryegrass and white clover (Trifolium repens L.) pasture experiment at Lincoln University, with two levels each of irrigation and nitrogen fertiliser.

At all three lysimeter sites, the pasture production was nitrogen-limited, with herbage yields of 10.8-14.9 t DM/ha/y, below optimum yields achievable for Canterbury. The results suggested under-fertilisation of pasture to be prevalent across the region. ‘DairyMod’ was successful in accurately simulating pasture growth under a commercial dairy operation when compared with the measured...
lysimeter data. However, limitations within the model were identified. Specifically, the calibrated model failed to account for the mechanistic relationship between nitrogen and leaf extension at the temperature stress parameter values required to achieve a reasonable fit with the observed data. Accordingly, within the model, temperature became more limiting than nitrogen. However, this was able to be overcome through the reliance on the empirical relationship between temperature stress and photosynthesis whereby temperature stress functions in the model could be manipulated to achieve the ‘correct’ yields.

‘HYDRUS-1D’ was found to be superior to ‘DairyMod’ in the simulation of soil water flow. This was due to the closer predictions of drainage and soil moisture content with that observed compared with DairyMod. The simulated drainage highlighted issues in the lysimeter design. Where lysimeters were installed without rubber rims around the top of lysimeter casings, there was the potential for surface redistribution of water to occur. This ultimately led to discrepancies in the lysimeter data through unaccounted for water losses and therefore a reduction in drainage.

A crop coefficient time series was developed from the lysimeter water use data. The time step over which water use measurements were made was the dominant contributing factor to variation in monthly crop coefficient values between lysimeter sites. When daily estimates of water use are used rather than weekly or greater, which were calculated with the SWW model, the spatial variability was largely eliminated. Temporal variations were found to be seasonally driven. When a mean crop coefficient time series from the three lysimeter sites was used to predict PET, estimates were within 1-11% of the actual evapotranspiration (AET), determined using the observed lysimeter data. When used to predict PET in the Lincoln experiment, estimates were within 3-13% of AET when water was not limiting. The results highlighted that, due to temporal variations, use of a single crop coefficient value could not be supported, which led to the rejection of the null hypothesis. However, the site averaged time series could be used for water allocation management purposes over the irrigation season months.

The single layer PM, PM\textsubscript{FAO} and PT models over predicted water use. There was a strong systematic error to the daily PM estimates. When the canopy was small PM under-estimated AET but at a leaf area index greater than approximately 1.3, PM over-estimated AET. This led to total over-estimations of 8-29%. However, this was an improvement on the climate-based PM\textsubscript{FAO} predictions, which over-estimated AET by 31-58%, and the PT model, which over-estimated AET by 17-30%. The failure of these methods to accurately predict water use was due to their inherent assumptions of the canopy that are not representative of a typical grazed ryegrass pasture in Canterbury. The dual crop coefficient model provided estimates of water use within 1-24% of the observed AET. However, the SWW model predicted water use within 9% of AET. This was largely owing to the separation of soil evaporation from canopy transpiration, enabling the influence of the canopy on the potential soil evaporation to
be adequately accounted for. These results highlighted the benefit of using the SWW model for irrigation management purposes over other PETc models and the need to actively account for the canopy, being the primary factor controlling water use. The method of estimation was also found to be significant, whereby under a grazed system the process of canopy transpiration needs to be separated from the soil evaporation.

Finally, irrigation schedule scenario testing across the three lysimeter sites indicated ~35% of drainage losses could be avoided through optimising irrigation scheduling. Doing so involved applying 10-20 mm per irrigation event, with a minimum return interval of 2-4 days, and delaying irrigation by 10-14 days following grazing of the paddock. Through optimising irrigation, the total irrigation applied was reduced by up to 64% without compromising herbage accumulation. However, while less irrigation was required, more nitrogen was necessary for optimum yields to be achieved. It is likely that this finding is applicable to many commercial dairy farms region wide.

**Keywords:** evapotranspiration, lysimeter, perennial ryegrass, nitrogen, irrigation, crop coefficient, Penman-Monteith, Priestley-Taylor, Shuttleworth-Wallace, DairyMod, HYDRUS.
Dedication and Acknowledgements

This thesis is dedicated to the memory of two great men: my first husband Nello Donaggio and my primary supervisor Professor Graeme Buchan. Nello was my greatest encourager when I first made the step towards a post-graduate degree and helped me to believe in my ability to succeed. Graeme’s kindness, faith, and passion for soil physics and the environment captivated me during my undergraduate degree and drew me back to Lincoln University, with the knowledge that I would be well supported in my research.

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### Abbreviations

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<td>BC</td>
<td>Blaney-Criddle method</td>
</tr>
<tr>
<td>C1</td>
<td>Channel 1</td>
</tr>
<tr>
<td>C2</td>
<td>Channel 2</td>
</tr>
<tr>
<td>C3</td>
<td>Channel 3</td>
</tr>
<tr>
<td>CO\textsubscript{2}</td>
<td>Carbon dioxide</td>
</tr>
<tr>
<td>CV</td>
<td>Coefficient of variation</td>
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<tr>
<td>DCC</td>
<td>Dual crop coefficient</td>
</tr>
<tr>
<td>DMod</td>
<td>DairyMod</td>
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<tr>
<td>ET</td>
<td>Evapotranspiration</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agriculture Organisation</td>
</tr>
<tr>
<td>FC</td>
<td>Field capacity</td>
</tr>
<tr>
<td>FWE</td>
<td>Farm working expenses</td>
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<tr>
<td>Hg</td>
<td>Hargreaves method</td>
</tr>
<tr>
<td>HM</td>
<td>Herbage mass</td>
</tr>
<tr>
<td>I\textsubscript{act}</td>
<td>Actual irrigation water applied</td>
</tr>
<tr>
<td>I\textsubscript{opt}</td>
<td>Optimised irrigation</td>
</tr>
<tr>
<td>I\textsubscript{sim}</td>
<td>Simulated irrigation</td>
</tr>
<tr>
<td>L1</td>
<td>Lysimeter 1</td>
</tr>
<tr>
<td>L2</td>
<td>Lysimeter 2</td>
</tr>
<tr>
<td>L3</td>
<td>Lysimeter 3</td>
</tr>
<tr>
<td>LDF</td>
<td>Larundel Dairy Farm</td>
</tr>
<tr>
<td>LTM</td>
<td>Long term mean</td>
</tr>
<tr>
<td>MAE</td>
<td>Mean absolute error</td>
</tr>
<tr>
<td>MBE</td>
<td>Mean bias error</td>
</tr>
<tr>
<td>MBIE</td>
<td>Ministry of Business, Innovation and Employment</td>
</tr>
<tr>
<td>MS</td>
<td>Milk solids</td>
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<tr>
<td>MSD</td>
<td>Mean square deviation</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>NIWA</td>
<td>National Institute of Weather and Atmospheric Research</td>
</tr>
<tr>
<td>NRMSED</td>
<td>Normalised root mean square deviation</td>
</tr>
<tr>
<td>NSE</td>
<td>Nash-Sutcliffe efficiency coefficient</td>
</tr>
<tr>
<td>O</td>
<td>Observed (data/value)</td>
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<tr>
<td>P</td>
<td>P-value</td>
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<tr>
<td>PED</td>
<td>Potential evapotranspiration deficit</td>
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<td>PF</td>
<td>Pendo Farms</td>
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<tr>
<td>PM</td>
<td>Penman-Monteith method</td>
</tr>
<tr>
<td>PM\textsubscript{FAO}</td>
<td>FAO-Penman-Monteith method</td>
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<tr>
<td>PT</td>
<td>Priestley-Taylor method</td>
</tr>
<tr>
<td>Rg</td>
<td>Growth respiration</td>
</tr>
<tr>
<td>RG</td>
<td>Ryegrass</td>
</tr>
<tr>
<td>RAW</td>
<td>Readily available water</td>
</tr>
<tr>
<td>RMSD</td>
<td>Root mean square deviation</td>
</tr>
<tr>
<td>RPM</td>
<td>Rising plate meter</td>
</tr>
</tbody>
</table>
S  Sink term in the Richards equation, Simulated (data/value)
SEM  Standard error of the mean
SMC  Soil moisture content
SS  total sum of squares
SWW  Shuttleworth Wallace
TAW  Total available water
TDR  Time domain reflectometry
TDT  Time domain transmission
Th  Thornthwaite method
TSD  Three Springs Dairies
TY  Total yield
WC  White clover
WSC  Water soluble carbohydrates
VCN  Virtual climate network
WMO  World Meteorological Organisation
WP  Wilting point

Symbols

A  Energy fluxes leaving the crop and substrate as sensible heat (MJ/m² ground area)
A_s  Energy flux leaving the substrate as latent heat (MJ/m² ground area)
AET  Actual evapotranspiration (mm)
AET_{daily}  Actual evapotranspiration (mm/d)
AET_{obs}  AET calculated using observed drainage data (mm)
AET_{pot}  AET calculated using HYDRUS-simulated drainage data (mm)
a  Intercept
b  Fitting constant in Brooks and Corey (1966) model, slope of the least squared regression
b(x)  Normalised water uptake distribution function (mm⁻¹)
C  Actual atmospheric CO₂ concentration (µmol/mol)
C_c  Canopy weighing coefficient
C_p  Specific heat of the air (MJ/kg/°C)
C_s  Soil weighing coefficient
CR  Capillary rise (mm)
D  Drainage (mm), Vapour pressure deficit (mb)
DM  Dry matter (t/ha, kg/ha)
e_a  Actual vapour pressure (kPa)
e_s  Saturation vapour pressure (kPa)
E  Evaporation (mm)
E_{pot}  Potential evaporation (mm)
f_{ew}  Exposed and wetted soil fraction
f_g  Live ground cover fraction
g  Pasture growth (kg C/m²/d)
G  Soil heat flux (MJ/m²/d), Net growth rate (kg C/m²/d)
GAI  Green area index of pasture above the residual grazing height (m²/m², -)
g_{water}  Available soil water as a function of WP
h  Canopy height (mm), pressure head (mm, kPa)
h_A  Minimum pressure head allowed at the surface (mm, kPa)
h_m  Maximum canopy height (mm)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tr>
<td>$h_s$</td>
<td>Maximum pressure head allowed at the surface (mm, kPa)</td>
</tr>
<tr>
<td>$h_o$</td>
<td>Osmotic head (mm)</td>
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<tr>
<td>$H_{evap}$</td>
<td>Actual water available for evaporation (mm)</td>
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<tr>
<td>HGR</td>
<td>Herbage growth rate (kg DM/ha/d)</td>
</tr>
<tr>
<td>I</td>
<td>Irrigation (mm)</td>
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<td>$K$</td>
<td>Hydraulic conductivity (mm/d)</td>
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<td>$K_c$</td>
<td>Crop coefficient</td>
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<tr>
<td>$K_{AET}$</td>
<td>Crop coefficient developed from observed lysimeter AET data</td>
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<td>Crop coefficient developed by Bright (2009a)</td>
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<td>$K_{FAO}$</td>
<td>Crop coefficient developed by FAO</td>
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<td>Upper limit crop coefficient</td>
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<td>$K_{cb}$</td>
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<td>$K_{rel}$</td>
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<td>LAI</td>
<td>Leaf area index (m²/m², -)</td>
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<td>LAI_{active}</td>
<td>Active leaf area index (m²/m², -)</td>
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<td>LAI_{cept}</td>
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<td>LAI at half the maximum pasture height (m²/m², -)</td>
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<td>LC</td>
<td>Lack of correlation (%)</td>
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<td>LER</td>
<td>Leaf extension rate (mm/°Cd)</td>
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<td>$L_R$</td>
<td>Rooting depth (mm)</td>
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<td>Maintenance respiration coefficient (d⁻¹)</td>
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<td>n</td>
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<td>N%</td>
<td>Herbage nitrogen concentration (%)</td>
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<tr>
<td>N_{act}</td>
<td>Actual nitrogen concentration (%)</td>
</tr>
<tr>
<td>NNI</td>
<td>Nitrogen Nutrition Index</td>
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<td>N_{opt}</td>
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<td>$N_{ref}$</td>
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<td>Rate of water inflow/outflow of water (mm/d)</td>
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<td>PAR</td>
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<td>PAW</td>
<td>Plant available water (mm)</td>
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<td>Potential evapotranspiration (mm/d)</td>
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<td>PET_c</td>
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<td>Canopy transpiration in the SWW function (mm/d)</td>
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<td>PM_s</td>
<td>Soil surface evaporation in the SWW function (mm/d)</td>
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<tr>
<td>PMSL</td>
<td>Atmospheric pressure above mean sea level (kPa)</td>
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</table>
PPF  Photosynthetic photon flux ($\mu$mol photons/m$^2$)
PSMD  Potential soil moisture deficit (mm)
P$_L$  Leaf gross photosynthesis ($\mu$mol CO$_2$/m$^2$ ground/s)
q  Soil water flow (mm/d), curvature parameter
r$_a$  Aerodynamic resistance (s/m)
r$_{a2}$  Aerodynamic resistances between the canopy and the reference height (s/m)
r$_{a3}$  Bulk boundary layer resistance per unit area of vegetation (s/m)
r$_{a4}$  Bulk stomatal resistance of the canopy (s/m)
r$_{s}$  (Bulk) surface resistance (s/m), also referred to as crop or canopy resistance
r$_{s3}$  Aerodynamic resistances between the soil surface and canopy (s/m)
r$_{s4}$  Surface resistance of the soil (s/m)
Ra  Extra-terrestrial radiation (MJ/m$^2$/d)
Rc  Aerodynamic resistance (s/m)
RH  Relative humidity (%)
RH$_{min}$  Daily minimum relative humidity (%)
R$_e$  Solar radiation (MJ/m$^2$/d), Substrate resistance (s/m)
R$_{so}$  Clear sky solar radiation (MJ/m$^2$/d)
R$_m$  Canopy maintenance respiration ($\mu$mol CO$_2$/m$^2$/s/°C)
R$_N$  Respiratory cost of N acquisition (kg N/m$^2$)
R$_n$  Net radiation (MJ/m$^2$/d)
r$^2$  Coefficient of determination
r$_1$  (Bulk) stomatal resistance (s/m)
RO  Runoff (mm)
SB  Squared bias (%)
Se  Effective saturation
SF  Subsurface flow (mm)
t  time (d, min, s)
T  Air temperature (°C)
TAGR  Temperature growth rate (kg DM/ha/°Cd)
T$_{act}$  Actual transpiration (mm)
T$_b$  Base air temperature (for pasture growth) (°C)
T$_{demand}$  Actual transpiration demand (mm)
T$_{mean}$  Mean daily temperature (°C)
T$_{mn}$  Minimum daily air temperature (°C)
T$_{mn,high}$  Maximum or full low temperature stress function (°C)
T$_{mn,low}$  Initial low temperature stress function (°C)
T$_{mx}$  Maximum daily air temperature (°C)
T$_{mx,high}$  Maximum or full high temperature stress function (°C)
T$_{mx,low}$  Initial low temperature stress function (°C)
T$_{opt}$  Optimum daily air temperature (°C)
T$_{pot}$  Potential transpiration (mm)
T$_{ref}$  Reference daily air temperature (°C)
T$_{sum,high}$  Critical temperature sum for recovery from high temperature stress (°C sum)
T$_{sum,low}$  Critical temperature sum for recovery from low temperature stress (°C sum)
T$_t$  Thermal time (°Cd)
u$_2$  Wind speed at 2 m (m/s)
\( V \) Volume of water (mm\(^3\))

\( w \) Mass wetness of the soil (i.e. ratio of water mass to dry mass)

\( W \) Shoot mass (kg C/m\(^2\))

\( \text{WUE} \) Water use efficiency (kg DM/ha/mm water)

\( X \) Spatial coordinate (mm)

**Greek symbols**

\( \alpha \) Photosynthetic efficiency, Priestley-Taylor empirical coefficient, angle between the direction of flow and the vertical axis in the Richards equation (\(^\circ\)), inverse of air entry suction in the van Genuchten (1980) model (1/cm)

\( \alpha(h) \) root-water uptake water stress response function

\( \alpha_{\text{amb,15}} \) Photosynthetic efficiency at ambient CO\(_2\) concentration and 15°C

\( \Delta \) Slope of the saturation vapour pressure temperature relationship (kPa °C\(^{-1}\))

\( \delta \) Soil layer thickness (m)

\( \theta \) Volumetric water content (v v\(^{-1}\))

\( \theta_{\text{WP}} \) Volumetric water content at wilting point (v v\(^{-1}\))

\( \theta_{\text{FC}} \) Volumetric water content at field capacity (v v\(^{-1}\))

\( \theta_c \) Volumetric water content at the critical capacity (v v\(^{-1}\))

\( \theta_r \) Residual volumetric water content (v v\(^{-1}\))

\( \theta_s \) Saturated volumetric water content (v v\(^{-1}\))

\( l \) Pore connectivity parameter

\( I_e \) Total PPF incident on leaves (µmol photons/m\(^2\)/s)

\( \lambda \) Latent heat flux (MJ/m\(^2\)/d)

\( \xi \) Curvature parameter

\( \rho_a \) Mean air density at constant pressure (kg m\(^{-3}\))

\( \rho_{\delta} \) Dry bulk density of the soil (kg m\(^{-3}\))

\( \rho_w \) Density of water (kg m\(^{-3}\))

\( \gamma \) Psychometric constant (kPa/°C)

\( \psi_e \) Air entry water suction (kPa)

\( \omega \) Water stress index (-)

\( \omega_c \) Critical value of the water stress index (-)
Chapter 1
Introduction

1.1 General Introduction

This study forms part of the Waterscape Programme funded by the Ministry of Business, Innovation and Employment (MBIE). The objective of the Waterscape Programme is to develop a scientific basis for the integrated management of surface water and groundwater in New Zealand, with a specific focus on water-limited regions, such as Canterbury. The overall aim is to answer key questions with regard to water availability, water allocation and distribution, and climate and land use changes. The Waterscape Programme is being headed by three surface water and groundwater research groups in New Zealand: NIWA, Aqualinc Research Limited and GNS Science, with support from numerous others. The focus of the research in this thesis has stemmed from the objectives of the Waterscape programme; specifically, to improve estimates of water use to inform water management decisions.

The current research focuses on pasture water use, or evapotranspiration, for irrigated dairy pastures in Canterbury (Section 1.3).

The research was initially structured for a Master of Applied Science degree based around a network of nine drainage lysimeters located across three commercial dairy farms in Canterbury. Each site was supported by a meteorological station. Measurements of canopy development at one of the three sites enabled the direct comparison of lysimeter-grown perennial ryegrass (*Lolium perenne* L.) pasture with that grown in the wider paddock and with other published data for Canterbury. The lysimeters at all three sites enabled actual evapotranspiration to be determined, and compared with estimations of potential crop evapotranspiration using a number of standard evapotranspiration models. However, the lack of canopy data (i.e. leaf area and height data) at two of the three sites limited the ability for a number of the models to be applied. It also restricted the ability to understand spatial variations in water use. Therefore, at the end of 2013, the programme was upgraded to a PhD study. The intention was to build on initial findings through incorporation of pasture growth and soil water flow modelling. To assist this, an independent two-year data set, collected under controlled field experimental conditions with treatments of irrigation and nitrogen, was used. The combined datasets enable a greater understanding of evapotranspiration and its estimation on the Canterbury Plains to be gained.
1.2 Evapotranspiration

Evapotranspiration encompasses evaporation of water from the soil surface and plant transpiration. Temporal variations in evapotranspiration, both worldwide (Frank & Inouye, 1994) and within New Zealand (Ryan, 1987) are climate driven. Spatially, evapotranspiration has the potential to vary in response to climate as well as the soil conditions and management. Soil type, for example, can influence the water holding capacity of a soil and therefore water availability to the plant and the potential for water losses, including drainage and surface re-distribution. Management practices, including irrigation, fertilisation and grazing, can also lead to spatial variations in evapotranspiration through their influence on pasture growth.

The current hypothesis is therefore that there is sufficient spatial variation in pasture water use to preclude the use of a single crop coefficient time series at all locations for accurately modelling evapotranspiration from pasture for the purpose of irrigation management.

1.3 Irrigation demand in Canterbury

The Canterbury region is the largest consumptive user of water in New Zealand. Southland has a greater total water use, but the majority (99%) is for hydroelectricity generation (Rajanayaka et al., 2010). Within Canterbury, irrigation is the dominant water consumer, and in 2010 accounted for 72% of the region’s consented annual water allocation for the irrigation of 680,128 ha. This equated to 68% of the potentially irrigable area in Canterbury (Morgan et al., 2002) and over 60% of the country’s total consented irrigated area (Rajanayaka et al., 2010). Of the 680,128 ha, 87% was irrigated pasture with the remainder split between arable cropping, horticulture, and viticulture. Irrigated pasture is therefore the significant land use within the region. Accordingly, access to water for irrigation is a key driver of the local and national economy through the large increases in production that can be achieved with it (Saunders & Saunders, 2012). However, with many water resources in the region becoming, or already considered, fully allocated (Jenkins, 2007) there is increasing pressure to manage water more effectively.

Despite its importance, understanding of evapotranspiration from irrigated dairy pasture in Canterbury has to date been relatively limited. Without a scientifically robust understanding of pasture evapotranspiration, there is the potential for seasonal irrigation allocations, which are required to form part of irrigation water permits (Ministry for the Environment, 2011), to be either under- or over-estimated. This can lead to production losses due to insufficient allocation, or conversely the ‘locking up’ of water through over-allocation. This is of particular importance where irrigation demand is high, such as in Canterbury, but where further irrigation developments are largely restricted due to existing pressures on water resources (Morgan et al., 2002).
Models commonly used to estimate evapotranspiration include the Penman-Monteith combination model (Monteith, 1965), or other derivatives or simplifications of it. Some of these are the Priestley-Taylor radiation-based model (Priestley & Taylor, 1972), the FAO-56 dual crop coefficient method (Allen et al., 1998), and the coupled multi-layer approach of Shuttleworth and Wallace (1985). However, their validity in a New Zealand context, and more specifically Canterbury, under different canopy conditions due to grazing effects, has not been evaluated. Furthermore, current methods used in the estimation of farm-scale evapotranspiration practised by regional councils place significant focus on soil properties, namely the soil plant available water (PAW), with little regard for the influences of the canopy, as to date such influences, specifically under a grazed scenario, have not been well researched.

This thesis therefore aims to improve understanding of evapotranspiration from ryegrass-based irrigated pastures under grazing. To do this, quantitative relationships between actual evapotranspiration and canopy development have been identified. Methods commonly applied in the estimation of potential canopy evapotranspiration were examined to determine their validity within a Canterbury context, under grazing. The findings from this are intended to inform farm-scale water allocation and management decisions, which in aggregate aims to improve allocation and management decisions at the regional scale.

1.4 Aims and objectives

As this study forms part of the MBIE Waterscape Programme (Section 1.1), the experimental design and much of the data collection were not exclusive to the research of this thesis. Namely, the results presented in Chapters 3-4 relate to the Waterscape Programme. The data presented in Chapter 5 were collected for a separate Lincoln University Research project investigating water use efficiency of ryegrass-based pastures in Canterbury. However, these datasets are used exclusively as a modelling control for this thesis.

The main aim of this research is to improve estimates of irrigated, grazed pasture evapotranspiration in Canterbury through the evaluation and validation of existing models. The desired outcome is to provide a scientifically robust and defensible basis for water allocation and water management decisions. To achieve this, the following objectives were set:

1. Critically review current methods used for estimating potential evapotranspiration.

2. Describe and quantify growth of a well-watered lysimeter-grown perennial ryegrass-based pasture under a commercial Canterbury dairy farming operation. This will allow for the direct comparison of pasture performance with other published data for Canterbury, and provides data
against which simulated pasture growth can be validated (Objective 3), and leaf area and pasture height data required for the estimation of pasture water use (Objective 4).

3. Assess the potential of ‘DairyMod’ to accurately simulate growth of perennial ryegrass-based dairy pasture when compared with irrigated lysimeter-based measurements on a commercial Canterbury dairy farm.

4. Describe and quantify lysimeter drainage, soil moisture and actual evapotranspiration of lysimeter-grown ryegrass pasture on three irrigated commercial Canterbury dairy farms.

5. Determine the accuracy with which two common models, ‘DairyMod’ and ‘HYDRUS-1D’, can be used to simulate soil water flow when compared with lysimeter-based drainage and soil moisture measurements for three irrigated commercial Canterbury dairy farms.

6. Develop and assess a crop coefficient time series for irrigated pasture and assess the accuracy of current models used in the estimation of potential evapotranspiration when compared with lysimeter-based measurements on three irrigated commercial Canterbury dairy farms.

7. Validate selected pasture growth, soil water flow and potential evapotranspiration models against measured data collected from a controlled research site subjected to different water and nitrogen treatments.

8. Investigate how irrigation of pasture can be managed to improve irrigation efficiency and on-farm productivity.

These objectives were achieved through field lysimeter studies of water use at three sites across Canterbury over a 12-month period (September 2011-August 2012). Measurements of pasture canopy growth and development were carried out at one of these sites for the same period, and water use and canopy development data collected from a water use efficiency experimental trial from 2011-2013 (Black & Murdoch, 2013) at Lincoln University, Canterbury. Models used to simulate pasture growth, variably saturated soil water flow and daily evapotranspiration were used to support and extend the field collected data.

1.5 Thesis structure

This thesis is presented in seven chapters (Figure 1.1). A review of the literature is provided in Chapter 2. The literature review initially describes the process of evapotranspiration and explores the influences of climate, soil and pasture management and physiology on evapotranspiration. It outlines methods used to measure, quantify and simulate canopy development and variably saturated soil water flow. A critical review of methods employed in the measurement and estimation of evapotranspiration is then carried out to meet Objective 1.
Chapters 3-6 are designed to meet Objectives 2-8. Each chapter describes the experimental design, environmental conditions, methods and materials used, relevant to the specific chapter.

Chapter 3 addresses Objectives 2 and 3. Herbage mass, botanical composition, canopy leaf area and height and nitrogen fertility are quantified for lysimeter-grown ryegrass pasture at one of three Canterbury commercial dairy farms (Larundel Dairy Farm (LDF)) included in this thesis (Objective 2). The biophysical model ‘DairyMod’ is calibrated against the pasture measurements at LDF, then used to simulate pasture growth for the remaining two farms (Three Springs Dairies (TSD) and Pendo Farms (PF)) (Objective 3).

The results and a discussion of lysimeter measured soil water flow and pasture water use data for LDF, TSD and PF are provided in Chapter 4, to address Objective 4. Drainage through and changes in soil moisture in the lysimeters at the three sites are simulated using ‘DairyMod’ and ‘HYDRUS’, which are calibrated against the lysimeter drainage measurements (Objective 5). Crop coefficient time series are also developed in Chapter 4 from the lysimeter data. The predictive abilities of standard potential evapotranspiration models to estimate potential evapotranspiration from irrigated, grazed pasture, through the incorporation of measured and simulated pasture canopy variables, are then also investigated (Objective 6).

The validation of the ‘DairyMod’ and ‘HYDRUS’ and selected potential evapotranspiration models and crop coefficient time series is addressed in Chapter 5, with data collected under a controlled, perennial ryegrass and white clover (Trifolium repens L.) pasture experiment. Its treatments were ±irrigation and ±nitrogen fertiliser, which addresses Objective 7.

A series of scenarios are tested in Chapter 6 (Objective 8) to determine how irrigation can best be managed to limit losses of water that do not contribute to pasture growth (drainage and evaporation) and therefore improve irrigation efficiency.

The final chapter, Chapter 7, provides a general discussion of the results of Chapters 3-6 and identifies key outcomes from the current research and areas for further investigation.
Figure 1.1 Flow diagram of thesis structure.
Chapter 2
Review of the Literature

2.1 Introduction

Soil, water, and plant processes and their interactions have formed the focus of many previous studies. The process of evapotranspiration (ET) is the transfer of water from vegetation and soil into the atmosphere and is therefore fundamental to such studies. Accordingly, ET is a critical factor for local and regional planning in terms of both water quality and quantity, to inform decisions around water catchment management, irrigation, water storage, and resource sustainability. Given its significance, many researchers have developed methods to estimate and measure ET, and subsequent studies have evaluated the accuracy of these.

This chapter reviews current literature regarding the process of ET. Processes involved in the measurement of actual evapotranspiration and the influencing factors of climate, plant growth and soil are described. It includes methods used to measure, quantify and simulate canopy development and variably saturated soil water flow. A critical review of standard methods applied to the estimation of evapotranspiration is provided. Finally, a summary of statistical procedures commonly used for analysing and evaluating modelled data is given.

This literature review is extensive because of the nature of the topic. Specifically, coverage of literature relating to the field experiments (i.e. pasture growth and soil-water-plant dynamics) and pasture growth, soil water flow and evapotranspiration modelling was necessary. Where available, New Zealand, and particularly Canterbury, examples have been used. In the absence of data for perennial ryegrass, examples from other temperate grasses (e.g. cocksfoot (*Dactylis glomerata*)) are given.

2.2 Evapotranspiration – an overview

The processes of evaporation from the soil and plant surface and plant transpiration occur simultaneously and according to Hillel (1998) cannot be easily separated, although their relative significance changes as a crop develops. When a crop has low biomass and the surface of the soil is wet, water is mainly lost through soil evaporation. However, as the pasture canopy develops, more of the soil surface is shaded, which causes the fraction of evaporation to decrease and the rate of transpiration to increase. At some point transpiration becomes the main component of ET (Allen et al., 1998). At a low leaf area index (LAI) of less than one, for example, the potential soil evaporation
component becomes significant. In contrast, at full coverage (i.e. 95% light interception) where maximum photosynthetic activity occurs, transpiration dominates (ASCE, 1996; Brougham, 1958).

ET is influenced by four main climate variables: solar radiation, air temperature, air humidity, and wind speed (Section 2.3.1). Other influencing factors include water availability, crop type and canopy characteristics, soil salinity, environmental aspects, management practices, and root depth (Allen et al., 1998). However, where soil water is available, the climate factors form the dominant influence.

2.2.1 Potential evapotranspiration

Evapotranspiration is commonly defined as the potential evapotranspiration (PET), which is the rate at which water would be removed from the plant and soil surfaces if water was not limiting (Jensen, 1983). Distinctions are also made between PET from a reference surface (PET₀) and PET from a field-grown crop (PETᵣ) (Allen et al., 1998; Doorenbos & Pruitt, 1975).

The reference surface used in PET₀ estimations is a hypothetical grass crop with specific characteristics. These include completely shading the ground, covering a large area, disease free, of uniform height (0.12 m), actively-growing, and with sufficient water availability (Penman, 1948; Penman, 1962). The only variables controlling PET₀ are climatic (i.e. solar radiation, temperature, relative humidity, and wind). PET₀ therefore represents the evaporative demand of the atmosphere irrespective of other non-climatic influences, including soil type, crop type and development, or management practices.

PETᵣ refers to evapotranspiration from a disease-free, well-watered, and fertilised crop grown in the field with no water restrictions, and is therefore equal to the crop water requirement. PETᵣ can be calculated using a combination of climate data, crop resistance factors, the soil-crop albedo (albedo), and air resistance factors, which can cause PETᵣ to differ from PET₀ despite the same climatic conditions. In this study, PETᵣ refers to the PET from a perennial ryegrass dairy pasture.

PET₀ and PETᵣ can be estimated from a number of standard models with climatic, soil and canopy variable inputs. Estimation of PETᵣ has been addressed in Section 2.4.

2.2.2 Actual evapotranspiration (AET)

Actual evapotranspiration (AET) refers to the amount of water that is actually removed from a surface or a soil profile through evaporation and transpiration (Pidwirny, 2006). AET may be a fraction of PET, or may equal PET, and is largely dependent on the availability of soil moisture. When soil water is not restricted, and plant diseases or nutrient deficiencies do not limit plant function, AET is usually equal to PETᵣ. As the soil water content reduces and becomes restricting, AET falls below PETᵣ and may even reach zero without inputs of irrigation or rainfall. However, even when water is not limiting, extreme temperatures and wind can result in an inability of the plant to keep up with demand and as a result, AET may fall below PETᵣ (Kramer, 1983) (Section 2.3.2.2).
2.2.2.1 Measurement of actual evapotranspiration

The measurement of AET from a crop involves detailed field measurements of energy or water fluxes. The eddy covariance technique, for example, is used for measuring vertical energy fluxes (Ding et al., 2010; Kuske, 2009), while lysimeters are used to measure water fluxes in, out, and through the soil (Allen et al., 1998; Hillel, 1998; Jensen et al., 1990). AET can therefore be determined through measurement of the various components of the soil water balance (Allen et al., 1998). In the current research, AET was determined using a standard water balance equation (Equation 2.1) with measured water fluxes of irrigation and precipitation, soil moisture and drainage. For the first experiment (Chapters 3 and 4), these were based on lysimeter measurements. For the second experiment in Chapter 5, measurements of water inputs and changes in soil moisture were coupled with simulated drainage predictions.

Soil water balance

The water balance approach encompasses the subtraction of water outputs from the inputs to calculate ET losses (Allen et al., 1998; Russell & Norman, 1959), as in Equation 2.1. Here, I is the irrigation, P the precipitation, RO the runoff, D the drainage, CR the capillary rise, ΔSF the change in subsurface flow, and ΔSMC the change in soil moisture content. In many situations, subsurface flow is minor, except on slopes. Furthermore, lysimeters consist of a soil profile encased in a non-permeable chamber; therefore, subsurface flow and capillary rise do not need to be considered.

\[ \text{ET} = I + P - RO - D + CR \pm \Delta SF \pm \Delta SMC \]  \hspace{1cm} 2.1

Numerous other authors have presented variations of Equation 2.1 for calculating ET, including Rose (2004), Jensen (1973), and Hillel (1998). However, all effectively follow a similar process.

Commonly, AET is estimated using neutron probes, time domain reflectometers and tensiometers, or similar technology (Black & Murdoch, 2013; Di et al., 1998; Dougherty, 1973; Mills, 2007). AET is determined from changes in the soil water content or soil water tension plus rainfall and irrigation water inputs using Equation 2.1. If not measured, drainage and surface runoff losses can be estimated to be equal to water inputs in excess of the water holding capacity of the soil, and capillary rise is often ignored.

Lysimeters

Lysimeters typically consist of large tanks filled with soil, either excavated and re-packed or as an undisturbed soil monolith, installed within the field to reflect natural conditions (Winter, 1974). The physical and biological properties of a re-packed lysimeter compared with one containing an undisturbed profile are very different, and therefore the World Meteorological Organization (WMO) (2008) recommends an undisturbed soil approach to their construction.
Two types of lysimeters are universally recognised: weighing lysimeters and drainage (non-weighing) lysimeters (Allen et al., 1998; Jensen et al., 1990; WMO, 2008). Weighing lysimeters relate the change of lysimeter mass to water loss, which is a measure of AET plus drainage losses. A drainage collection system enables separate measurement of the drainage losses (Hillel, 1998). Drainage lysimeters combined with instrumentation for measuring precipitation and soil moisture, allow for measurements of water inputs, outputs, and corresponding changes in the water content (Jensen et al., 1990). Once these are obtained, AET can be calculated using the water balance approach (Equation 2.1) for both short and longer time periods. Figure 2.1 illustrates a drainage lysimeter.

Figure 2.1 Illustration of a drainage lysimeter. Adapted from Perkins (2006).

Lysimeters provide one of the most effective and accurate means for measuring AET (Allen et al., 1998; ASCE, 1996). According to ASCE (1996), lysimeters allow AET to be accurately calculated over short time periods, down to half or one hourly intervals. Weighing lysimeters provide a greater degree of accuracy than non-weighing lysimeters (ASCE, 1996), with smaller measurements able to be obtained over short time periods (Allen et al., 1998). However, several weaknesses associated with both weighing and drainage lysimeters have been identified, some of which can result in calculation errors.

The required expertise and high cost associated with lysimeter installation and associated measurement devices are considered to provide the greatest limiting factors for their use (Allen et al., 1998; McLaren & Cameron, 1996; WMO, 2008). Winter (1974) identifies a common weakness attributed to lysimeters as the separation of the soil within the tank from the surrounding soil and subsoils, affecting the soil water potential, for example, through restricted drainage. However, this can be avoided by artificially maintaining suction at the lysimeter base (WMO, 2008). Another weakness is that they only provide a measure of ET for a limited plant sample size (ASCE, 1996); hence it is important to match the lysimeter vegetation with the surrounding vegetation. The confinement of the soil may also act to restrict the extent of root development of the plants, although this is limited to
plants with large, deep roots (Jensen, 1983; Winter, 1974; WMO, 2008). Lysimeters can also be affected by temperature changes, which can lead to weight changes that are not associated with actual increases or decreases in the soil moisture (Black et al., 1968; Harrold & Dreibelbis, 1958). However, the influence of such temperature changes are considered to be negligible. In the current research, drainage lysimeters were installed in the field as undisturbed soil cores. The existing ryegrass pasture vegetation was maintained, a rooting depth of 700 mm was allowed for, and fibreglass wicks were installed at the lysimeter base where restricted drainage was considered possible (Section 4.2.1.1).

Lysimeters have been widely used in New Zealand and particularly in Canterbury in research associated with nitrogen and contaminant transport (Cameron & Di, 2004; Cameron et al., 2002; McLeod et al., 2008; McLeod et al., 2001), groundwater recharge (Barkle et al., 1998; Evans, 1999; Thorpe & Scott, 1999), and canopy evapotranspiration (Annett, 1949; Clothier et al., 1982; Green et al., 1984). Each of these typically involved 1-4 lysimeter replicas per treatment. Where a single lysimeter was used it was generally a more precise weighing lysimeter (Green et al., 1984). Cameron et al. (1992) provided a standardised method for installing drainage lysimeters, which has been followed in this study. In brief, the method involves digging around a metal cylinder casing and progressively pushing it down over the exposed soil column, leaving the soil inside the cylinder undisturbed. A metal cutting plate is used at the base of the lysimeter to detach it from the underlying soil. Tension drainage systems, or alternatively a 50 mm layer of gravel, can be installed at the base to maintain natural drainage. Over this, a base plate with a drainage tube is attached and sealed onto the casing. Warm (~50°C) liquefied petroleum is used to seal the gap between the soil monolith and the inside casing edge to prevent edge flow. Typically lysimeters have a diameter of 500 mm and depth of 700 mm, although can range from 200-1200 mm diameter and up to 1200 mm deep. The lysimeters installed for this study were all 500 mm diameter and 700 mm deep. Three lysimeters per treatment site were installed, in accordance with standard practice (Cameron et al., 1992).

2.3 Climatic, soil and canopy influences on evapotranspiration

2.3.1 Climatic drivers of evapotranspiration

In a broad context, the energy required to enable the vaporisation of water is provided by solar radiation and air temperature. Air humidity and wind speed on the other hand provide the diffusive transfer mechanism for the removal of water from the evaporating surface. As the air temperature, solar radiation, and wind speed increase so too does ET. Conversely, as the air humidity increases, ET decreases (Allen et al., 1998).

Solar radiation provides the largest source of energy used in the ET process, supplying the latent energy required for conversion of liquid water at the evaporating surface to water vapour in the atmosphere.
The amount of solar radiation that reaches the evaporating surface depends on various factors including the sun’s elevation, the turbidity of the atmosphere, and the presence of clouds, which intercept the radiation.

Air temperature is controlled by solar radiation absorbed by the atmosphere and the heat emitted by the earth. As the air temperature rises, the available energy for vaporisation increases and more energy is transferred to the crop, which allows higher ET to occur.

Relative humidity is the amount of water vapour, at a given temperature, that is held in the air, relative to the maximum water vapour that the air could hold. The humidity gradient, being the difference between the vapour pressure at the evaporating surface and in the air immediately surrounding the evaporating surface, determines the potential for ET to occur. Under humid air conditions, the relative humidity is high and the humidity gradient is small. This results in little potential for further water to be stored by the atmosphere, and therefore a lower ET (Sentelhas et al., 2010).

Air movement transports the more humid air away from the evaporating surface, which becomes saturated through the evaporation and transpiration of water, and replaces it with drier air (Allen et al., 1998; Sentelhas et al., 2010).

### 2.3.2 Plant physiology and evapotranspiration

The following sections provide a description of perennial ryegrass pastures, which form the focus of the research in this thesis, followed by a discussion of the influences of water, temperature and nitrogen on pasture growth and evapotranspiration. Section 2.3.2 concludes with an overview of options for modelling pasture growth, and a detailed description of the DairyMod biophysical model.

#### 2.3.2.1 Perennial ryegrass (Lolium perenne L.) use and yields in New Zealand

Ryegrass is a ‘3-leaf’ plant in that only about 3 green leaves/tiller exist at any one time with the initiation of a new leaf coinciding with senescence of the oldest fourth leaf (Fulkerson & Donaghy, 2001).

Perennial ryegrass is widely used throughout New Zealand, largely owing to its ease of establishment and management, rapid recovery from grazing, adaptation to varying fertility and environmental conditions, compatibility with white clover, and high forage quality (Easton et al., 2001). It is a prolific tillering, compact grass with shallow roots, adapted to medium to high fertility, well-drained soils. Within New Zealand, its use is largely within lowland and hill areas, outside of the South Island high country. It does not perform well under drought conditions (Kemp et al., 1999)

Perennial ryegrass is characterised by a flush of growth during early spring (Kemp et al., 1999), but during hot, dry summers production can be poor (Brougham, 1959; Fasi et al., 2008). However, under irrigation, as in the current research, the effect of water stress can be avoided. The main flowering
period occurs in spring, with aftermath heading in summer. Flowering reduces the nutritive value of the pasture as the seed heads contain more structural material with lower nitrogen content (Lee et al., 2012; Tonmukayakul, 2009; Waghorn et al., 1989). Persistence can range from 5 to 20 years, depending on environmental factors such as pests, disease, and the ability to recover from summer drought conditions when irrigation is not used (Kemp et al., 1999).

Annually, perennial ryegrass dry matter production has been reported to range from 10 to 25 t DM/ha throughout New Zealand (Kemp et al., 1999). However, depending on location and environmental conditions, productivity can be lower. Fasi et al. (2008), found the production of unfertilised pastures to be approximately three times less than nitrogen-fertilised pasture. Easton et al. (2001) reported mean annual ryegrass yields of 10.9-14.1 t DM/ha based on a study that involved a range of cultivars grown in both the North Island and Canterbury. For Canterbury, mean annual yields were in the range of 11.7-13.2 t DM/ha. Horne et al. (2011) also reported irrigated ryegrass with white clover herbage yields, averaged over 30 years at Winchmore, Canterbury, to be 9.4-11.7 t DM/ha/y, depending on the amount of irrigation, return interval, and soil moisture trigger level set. The lower value of 9.4 t DM/ha/y involved a 15-day irrigation return interval, causing the top soil layer to be dry more frequently than in other treatments that had return intervals of 5 days. In the first experiment in this thesis, all lysimeters were spray irrigated with return intervals of 3-5 days. During the second experiment, irrigation return intervals were 3-60 days. Black and Murdoch (2013) recently reported maximum yields greater than 20 t DM/ha/y for the irrigated, fully fertilised ryegrass/white clover pasture in Canterbury, which were used to validate models in this research (Objective 7).

Average seasonal growth rates of perennial ryegrass have also been reported throughout the literature. Rickard and Radcliffe (1976) reported irrigated ryegrass growth rates for Winchmore, Canterbury to be between 3-56 kg DM/ha/d, with peak rates achieved during December and January, and the lowest growth period from June to August. Similarly, McBride (1994) reported, that when irrigated at a deficit of 50% of the available soil moisture, growth rates were 8-51 kg DM/ha/d for Winchmore. Ryegrass growth rates in the Bay of Plenty and Waikato reported by Baars et al. (1991) were higher, ranging from 5 kg DM/ha/d in July to 90 kg DM/ha/d in January.

Measurement of pasture herbage mass is commonly undertaken by destructive sampling or non-destructively estimated using a rising plate meter (RPM) (Michell, 1982), both of which were used in this study.
2.3.2.2 Influence of water

Soil water and plant interactions

Soil-water-plant relationships are complex. Soil water moves from regions of higher to lower water potential under the influences of gravity, suction, or osmosis (Jensen, 1983).

Saturated flow occurs when all pores are water-filled. Water will predominantly flow downwards under gravity, although some lateral flow can also occur. Following heavy rain or irrigation, the soil will drain until field capacity (FC) is reached, which is generally described as being equivalent to a matric potential of approximately -10 kPa (McLaren & Cameron, 1996). At this point AET, in theory, is equal to PET, as water is not limiting.

When unsaturated, water is held within the soil matrix by adhesion and cohesion forces. As soil dries, the larger then progressively smaller pores become air-filled (Hillel, 1998), causing suction to increase. Unsaturated flow occurs as either water creep along the larger soil pore walls, or as tube flow through narrow water filled micro pores (Hillel, 1998). As water is taken up by the plant, drier zones of lower potential occur around the roots, attracting water from wetter regions in the soil. If transpiration continues without inputs of rainfall or irrigation, the soil will continue to dry out and the soil water potential will further reduce. Eventually the flow of water will not be fast enough to meet the evaporative demand and the plant will come under water stress (McLaren & Cameron, 1996).

Various attempts have been made to determine the plant stress factor (K_s) as a function of the soil available water content. Allen et al. (1998) identified that the effect of water stress on ET can be represented as follows, where K_c represents a crop coefficient (Section 2.4.1):

\[
AET = K_s \times K_c \times PET = K_s \times PET_c
\]

Figure 2.2 illustrates the relationship between water stress and soil water content. A K_s < 1.0 indicates plant water stress. Various authors have identified that the stress point, which is commonly referred to as the critical deficit, varies depending on meteorological conditions (Doorenbos & Pruitt, 1975; Hillel, 1998), crop type (Van Bavel, 1966), and rooting densities (Cowan, 1965; Kirkham, 2005). The soil type is also, and predominantly, influential (Doorenbos & Pruitt, 1975). Lighter soils, such as sandy soils, dry out faster compared with heavier soil, which due to capillary forces are able to hold onto water under greater suction (McLaren & Cameron, 1996) (Section 2.3.3). The critical deficit (θ_c) is often considered to be where the plant available soil water (PAW) (i.e. field capacity - wilting point) falls below 50%, at which point the canopy is subject to water stress (Martin et al., 2008; Meyer & Green, 1981). The wilting point is generally described as being equivalent to a matric potential of approximately -1500 kPa (McLaren & Cameron, 1996). McBride (1994) identified that where soil moisture levels were maintained above 50% of the available soil moisture, annual pasture yields increased by 80% over dryland yields. For this study, the critical deficit has been defined as being at
50% of the PAW. Water extraction by the canopy can also reduce under wet conditions, due to water logging and oxygen limitations (Feddes et al., 2001; Johnson, 2013a). This is illustrated in Sections 2.3.2.6 and 2.3.3.4.

![Diagram of Water Stress Coefficient (Ks)](image)

Figure 2.2 Water stress coefficient (Ks), where RAW is the readily available water, TAW the total available water, FC field capacity and WP wilting point. Redrawn from Allen et al. (1998). The critical soil moisture deficit (θc) is reached once Ks < 1.

**Plant response to water stress**

Water stress has been identified as one of the greatest limiting factors to the growth and persistence of plants (Hsiao, 1973; Jamieson, 2000). The response of plants to water stress is one of control, where the rate of water loss through the plant into the atmosphere is limited to reduce the plant growth rate, prevent dehydration, and ultimately death (Jamieson, 2000). Control measures include reduced turgor pressure in cells, increased stomatal resistance to water vapour loss, and reduced photosynthesis, each of which reduce pasture productivity and yield (Campbell & Turner, 1990; Hillel, 1998; Hsiao, 1973; Jensen, 1983; Martin et al., 1990). The control response of plants is reflected in methods for estimating ET rates from the canopy. For example, the Penman-Monteith evapotranspiration model (Section 2.4.2.1) incorporates a canopy resistance factor (rs), which is a function of stomatal resistance and the leaf area index (Section 2.3.2.4) (Allen et al., 1998).

Stomatal closure is commonly considered to be the main control process by plants to reduce water loss and therefore limit the effects of stress (Hsiao, 1973). Stomata open and close in response to a range of environmental conditions, although the water potential of the plant (i.e. cell turgidity) is the dominant influence (Hillel, 1998; Jamieson, 1986). Stomatal closure regulates transpiration losses in accordance with soil moisture uptake (Johns, 1978). Numerous studies have identified that the controlling response of plants to water loss by reducing the leaf area, through reduced elongation, reduced tiller density, leaf rolling or early senescence, has a greater effect than through stomatal...
closure (Jamieson, 1986; Johns, 1978). Underlying this argument is that the rate of transpiration decreases in response to increased stomatal resistance. However, this is countered by leaf temperature rise and a subsequent increase in saturated vapour pressure within the stomata, increasing transpiration.

Reduced turgor pressure in response to water stress has a direct effect on cell expansion, which in turn leads to reduced leaf elongation and therefore the development of smaller leaves (Hsiao, 1973). Where the leaf area is reduced below the optimum for light interception of 95%, a reduction in light interception, photosynthesis and therefore transpiration and growth will result (Brougham, 1958; Johns, 1978). However, a plant can be affected by water stress levels that are much lower than those required to cause wilting, as cell expansion is one of the plant processes most sensitive to stress, even when it is mild (Hsiao, 1973).

When the soil moisture reaches the critical deficit, the availability of water for plant uptake is reduced below PET, and the plant comes under stress. However, in conditions of extreme temperature and wind, for example, in Canterbury where high north west winds and temperatures of 30°C or greater can frequently occur (Scotter & Heng, 2003), sometimes the xylem cannot keep up with demand (Kramer, 1983) and the crop can become stressed even if the water supply is adequate.

Jones et al. (1980) reported reductions in yield of 20% and photosynthesis of 50% from field-grown, water-stressed perennial ryegrass pasture grown in Berkshire, England, when compared with irrigated treatments. Herbage yield and photosynthesis reductions were attributed to a lower leaf area caused by a decline in tiller numbers and reduced production and expansion of leaves, and subsequently, the radiation intercepted fell to 80%. Barker et al. (1985) found herbage yield of water-stressed ryegrass was only 8% of the yield from irrigated treatments caused by reduced tiller density and leaf extension and appearance rates. A perennial ryegrass experiment by Akmal and Janssens (2004) identified insufficient water supply for ryegrass dry matter production was more critical than insufficient nitrogen supply. This conflicts with the findings of Black and Murdoch (2013) and Mills et al. (2006), who found nitrogen to be the principal limiting factor (Section 2.3.2.4). However, low yields that seem to be a consequence of water stress may actually be in response to a shortage of nitrogen in the soil layers, from which an unirrigated canopy draws its water (Garwood & Williams, 1967; Robson & Parsons, 1978).

Results of studies undertaken within Canterbury have yielded similar results. Once soil moisture falls below the critical limiting deficit, dryland cocksfoot pasture production was found to reduce on average by 1.45%/mm (Mills et al., 2006). Above the critical deficit no reduction in yield occurred. For a period of 2 years from October 2003 to October 20005 this led to an average yield loss of ~28% for a dryland cocksfoot pasture compared with irrigated treatments. Black and Murdoch (2013) also found
ryegrass yield to be reduced by 25%, on average, under a dryland scenario, while Martin et al. (2006) reported dryland yield reductions of up to 47% compared with an irrigated pasture.

The effects of the canopy response to water stress on water use, and therefore evapotranspiration, have been reported throughout the literature. Black and Murdoch (2013) reported no differences in the water use efficiency (WUE), defined as the ratio of plant herbage mass to the total amount of water used (i.e. AET), between irrigated and dryland ryegrass treatments, with annual WUE of 22-24 kg DM/ha/mm. While the irrigated treatments used more water, they also yielded more herbage. In contrast, Martin et al. (2006) identified WUE to increase with decreased water application, and that WUE was maximal with no irrigation applied. However, this came at the cost of pasture productivity. Martin et al. (2006) therefore suggest a benchmark WUE for irrigated ryegrass in Canterbury of 20 kg DM/ha/mm. Earlier studies by Hayman and McBride (1984) and Rickard and McBride (1986) found much lower efficiencies for irrigated pasture in Canterbury of between 11-12 kg DM/ha/mm based on irrigating at 20-50% of the available soil moisture. However, in each of these studies, the WUE was based on the amount of water applied rather than used through evapotranspiration, and therefore did not account for water lost through drainage. Due to complexities in measuring AET (Section 2.2.2.1), climate-based estimates of PET (i.e. PET_o) are often used instead (Martin et al., 2006). In this study, WUE is defined as the slope of the regression of ryegrass herbage production against measured AET, which accounts for drainage losses.

2.3.2.3 Influence of temperature
The effect of temperature is to regulate plant processes that control the plant’s growth and water use. For example, temperature influences the rate of photorespiration, which in turn impacts on the rate of photosynthesis (White & Snow, 2012). At temperatures above the optimum for growth of C_3 species such as ryegrass, as photorespiration increases, photosynthesis decreases. Mitchell and Lucanus (1962) reported an optimum temperature range of 19-20°C for ryegrass pastures in New Zealand compared with 15-22°C by Oizumi H. et al. (1974) for cocksfoot pastures and a value of 30°C by Thornley (1998) for pastures in general. However, maximum values of no more than 23-25°C are typical. Peri et al. (2002b) identified that, for a cocksfoot pasture, increases in P_n (the light-saturated photosynthetic rate) of 1.6 µmol CO_{2}/m^{2}/s/°C occur from 10-19°C. The optimum temperature range is 19-23°C, above which the photosynthetic rate declines by 0.077 units per °C from 23-31°C, which is attributed to increased photorespiration and maintenance respiration with temperature. An optimum leaf area index of 5.0 was also found to decline to 2.3 with air temperature changes from 10-31°C (Peri et al., 2002b). Peri et al. (2002a) therefore suggested that when temperatures exceed 22°C, grazing rotation lengths should be shorter to maximise photosynthesis and avoid production losses.
**Thermal time (Tt)**

Because of the influence of temperature on growth, temperature is often used as the basis for the prediction of crop (i.e. pasture) production (McKenzie *et al.*, 1999), for example, through thermal time accumulation. Thermal time refers to the cumulative temperature above a base temperature ($T_b$), below which no growth occurs. In its simplest form, the method for thermal time accumulation is given as Equation 2.3 (Moot *et al.*, 2000).

$$Tt \ (°Cd) = \frac{(T_{mx} - T_{mn})}{2} - T_b$$  \  2.3

Here, $T_{mx}$ and $T_{mn}$ are the maximum and minimum daily air temperatures. When $T_{mn}$ falls below $T_b$ a sinusoidal function can be used to fit 8x3 hourly fractions of a day, excluding periods when $T_{mn}$ is less than $T_b$ (Jones & Kiniry, 1986). Moot *et al.* (2000) identified $T_b$ values for development of different temperate pasture species to range between 0°C and 5°C. Tonmukayakul (2009) found a $T_b$ of 0°C was appropriate for growth of different pasture species in Canterbury, but compared temperatures between 0°C and 8°C, while Mills (2007) identified a $T_b$ of 3°C for cocksfoot pasture growth in Canterbury. Below this range photosynthesis and pasture development will cease while higher $T_b$ values result in shorter thermal time requirements (Lu & Man, 2010; Moot *et al.*, 2000).

Tonmukayakul (2009) found that Tt herbage accumulation of a dryland ryegrass/white clover pasture averaged 4.1 kg DM/ha/°Cd in spring but reduced to 0.9 kg DM/ha/°Cd in the summer due to water limiting conditions, and 0.5 kg DM/ha/°Cd during the autumn/winter. However, nitrogen deficiency was found to have restricted ryegrass growth during the study. Comparatively, Mills (2007) reported Tt growth rates of up to 7.2 kg DM/ha/°Cd for cocksfoot pasture in Canterbury under fully irrigated and nitrogen-fertilised conditions.

### 2.3.2.4 Influence of nitrogen

Nitrogen (N) is essential to plants, forming a fundamental component of the chlorophyll molecule, which is responsible for photosynthesis (McLaren & Cameron, 1996). Nitrogen has also been identified as the principal limiting factor to pasture production (Black & Murdoch, 2013; Mills *et al.*, 2006; Robson & Parsons, 1978). Nitrogen increases photosynthetic efficiency and allows higher rates of photosynthesis and subsequently more herbage production per unit of water used compared with a pasture with a low N status (Moot *et al.*, 2008). For example, Robson and Parsons (1978) reported nitrogen to increase canopy net and gross photosynthesis of a ryegrass pasture by up to 50-75% at light intensities of up to 450 W/m², due to the reduced ability of nitrogen-deficient leaves to make use of intercepted light (Robson & Deacon, 1978). Similarly, Woledge and Pearse (1985) found nitrogen to increase the photosynthetic capacity of ryegrass pastures, whereby the net photosynthesis per unit area of leaves from fertilized swards was 50% greater than that of the unfertilized swards and increased linearly by a slope of 2.38 mg CO₂/dm²/h per 1 mg N/dm² at 250 W/m². Peri *et al.* (2002b)
identified a nitrogen leaf concentration of 2.6% to be the critical value below which photosynthesis is severely constrained for a cocksfoot pasture, while a concentration of 5.2% or greater was maximal, with a photosynthetic rate of 27.4 μmol CO₂/m²/s. From 5.2% to 2.6%, the photosynthetic rate decreased at an average rate of 3 μmol CO₂/m²/s for every 10 g N/kg DM. Below a nitrogen leaf content of 2.6%, the photosynthetic rate declined by 11.3 μmol CO₂/m²/s for every 10 g N/kg DM. The influence of N on the photosynthetic efficiency of a cocksfoot-based pasture in Canterbury, when other factors are non-limiting, is illustrated in Figure 2.3. At a nitrogen content of 2% the photosynthetic efficiency of a cocksfoot pasture was ~60%, which increased linearly to 100% at a nitrogen content of ~4% (Peri, 2002). A similar illustration for a perennial ryegrass pasture in the literature could not be found.

![Figure 2.3](image)

**Figure 2.3** Standardised rate of photosynthetic efficiency against nitrogen (N) percentage for cocksfoot grown under field conditions where other factors were non-limiting. Redrawn from Peri (2002).

The principal effects of nitrogen supply on growth are in relation to canopy expansion and therefore light interception. Accordingly, interruptions in the supply of nitrogen can inhibit leaf area expansion, for which Grindlay (1997) suggests there is some mechanism or mechanisms controlling the leaf area growth according to nitrogen availability. He suggested that some C₃ crops (e.g. wheat, *Triticum* spp.) will adjust their leaf nitrogen content to match the photosynthetic flux density during growth to maximise use of intercepted radiation. Fergusson (1999) reported leaf lamina responses in barley (*Hordeum vulgare* L.) to applied nitrogen fertiliser showed that the green area of the lamina was decreased to maintain a specific leaf nitrogen of 2 g N/m² leaf. Accordingly, the implication is that the effect of nitrogen content on herbage production is indirect, and that the effect of nitrogen supply on growth is mainly due to influences on leaf extension and therefore radiation interception (Grindlay, 1997). However, to date there are no data in the literature that quantify the leaf nitrogen response of perennial ryegrass to nitrogen supply.
Mills et al. (2009) found that where water was not limiting, actual water used from the profile of a nitrogen-deficient cocksfoot pasture followed the same temporal and spatial pattern as a fully nitrogen-fertilised pasture. However, the WUE was reduced from 33.5 kg DM/ha/mm to 15.5 kg DM/ha/mm due to pasture production being more than halved. Similar results have been reported by Black and Murdoch (2013) for a ryegrass/white clover pasture, whereby WUE was up to 28 kg DM/ha/mm for an irrigated, fully nitrogen-fertilised pasture compared with 20 kg DM/ha/mm for an irrigated, nitrogen-deficient pasture. McKenzie et al. (2006) reported that for an irrigated perennial ryegrass pasture, the highest WUE was achieved with applications of 75 to 100 kg N/ha every grazing or 150 to 200 kg N/ha every second grazing, from which WUE increased by 40-69% compared with a nitrogen-limited pasture.

Nitrogen nutrition index (NNI)

A nitrogen nutrition index (NNI) can be used to describe the extent of N deficiency in pastures. The NNI is the ratio of the measured nitrogen concentration (N_{act}) to the optimum nitrogen concentration (N_{opt}), being the nitrogen concentration the pasture sward requires to sustain non-limiting growth and biomass accumulation (Lemaire et al., 1989). The NNI enables a decrease in the N concentration of the pasture (N%) as yield accumulates, identified as tissue N dilution by Marino et al. (2004).

Equations used in the determination of N_{opt} and NNI, as given by Lemaire et al. (1989) and Mills et al. (2009) are as follows:

\[ N_{opt} (%) = 4.8 \times DM^{-0.32} \]

\[ \text{NNI} = \frac{N_{act}}{N_{opt}} \]

According to Farruggia et al. (2004) an NNI of <0.8 is indicative of nitrogen-limited conditions, which leads to reduced sward growth.

Marino et al. (2004) reported a reduction in the NNI for annual ryegrass grown from August-October from ~1.5 to 0.5 with the application of 250 and 0 kg N/ha, respectively, with a 60-65% reduction in herbage accumulation. Similarly, Mills et al. (2009) found the accumulated herbage yield of irrigated cocksfoot pasture with an NNI of ~0.3-0.7 was less than half that of an irrigated cocksfoot pasture with an NNI above 0.8.

Light interception and leaf area

Photosynthesis and biomass production are dependent on light or photosynthetically active radiation (PAR) interception, which in turn is controlled by the leaf area of the canopy. According to Akmal and Janssens (2004), tiller and leaf numbers of pastures are the major contributor to herbage production. As discussed, the leaf area can be controlled by the canopy according to the supply of nitrogen to maximise the use of intercepted light (Grindlay, 1997). The effect of nitrogen on leaf extension was
described by O’Brien (2010). Leaf elongation rates of perennial ryegrass pasture per tiller (LER/tiller) were found to be up to 28% higher when 100 kg N/ha was applied (1.00 mm/°Cd) compared with no nitrogen (0.78 mm/°Cd). Similarly, Akmal and Janssens (2004) reported increases of 13.6% and 13.2% in perennial ryegrass tiller and leaf numbers, respectively, when nitrogen was introduced, which ultimately led to a positive response between nitrogen and the leaf area.

The leaf area is often presented in the form of the leaf area index (LAI) which is defined as the unit area of leaf per unit area of ground below it, expressed as m² leaf area per m² ground area (Allen et al., 1998). Following defoliation of a canopy, the leaf area index is low (0.1-3.0) (Korte et al., 1982, 1984), but increases, in response to nitrogen availability, and will reach a critical LAI once canopy closure (i.e. 95% ground cover) is achieved (Brougham, 1958; Pearce et al., 1965). The LAI of pasture at full ground cover typically ranges between 3-5 (Allen et al., 1998). Brougham (1958) and Shuttleworth and Wallace (1985) suggest at an LAI of 4-5 the light interception will be 95%. Bircham and Hodgson (1983), however, identify that for a perennial ryegrass-based sward under grazing influences, the critical LAI is 2.3-4.7. This compares with the LAI of three found to represent the LAI of ryegrass at canopy closure (Akmal & Janssens, 2004). Once the critical LAI of a canopy is reached, maximum transpiration and photosynthesis occur (Brougham, 1958; Pearce et al., 1965).

Both destructive (Villalobos & Fereres, 1990) and non-destructive methods exist for determining LAI and light interception (Jonckheere et al., 2004). Non-destructive canopy measurements of pastoral type systems are difficult as, due to their low plant area, clumping effects, sky conditions, and soil albedo can significantly affect estimates of PAR (Jonckheere et al., 2004; Nouvellon et al., 2000). Destructive measurements of leaf area are therefore commonly used to calibrate, and overcome inaccuracies associated with non-destructive measurements (Mills, 2007). For this study, both non-destructive and destructive measurements of LAI were used.

The relationship of canopy LAI to evapotranspiration has been discussed in the literature, although no literature was found in regards to pasture. Figure 2.4 illustrates the general relationship of LAI to crop coefficients (Kc) (Section 2.4.1), based on measured lysimeter data for snap beans (Phaseolus vulgaris L.) (Wright, 1982). Essentially, as the canopy developed and the LAI increased, so too did transpiration, and therefore Kc. As the canopy reached maturity, senescence led to a lower Kc. Figure 2.4 also illustrates the effect of evaporation from the soil. In the early stages of canopy growth, when the soil was wetted, evaporation increased Kc. As the canopy developed, rainfall and irrigation events still led to increases in Kc, although to a lesser extent as canopy transpiration increased. Similarly, Villalobos and Fereres (1990) compared evaporation and transpiration versus LAI for maize (Zea mays L.), cotton (Gossypium hirsutum L.), and sunflower (Helianthus annuus L.) canopies and found significant interactions. At low LAI values, evaporation was the dominant process. For example, at an LAI of ~1.5, approximately half of the water loss was due to evaporation, while above 1.5 transpiration dominated.
Accordingly, where pastures are nitrogen-deficient, the leaf extension is reduced and therefore the amount of light intercepted by the canopy decreases, reducing the transpiration potential prior to canopy closure (Gastal & Durand, 2000; Grindlay, 1997; Johns & Lazenby, 1973). However, with a smaller leaf area, prior to canopy closure, there is greater potential for soil water evaporation (Van Keulen et al., 1989), particularly from an irrigated crop. Accordingly, a reduction in canopy transpiration due to a smaller leaf area can be offset by increases in soil evaporation, limiting the effect of N fertiliser on AET. Furthermore, once full cover is achieved, the canopy will transpire at the potential rate (Mills et al., 2006), diminishing the effects of nitrogen on canopy evapotranspiration.

2.3.2.5 Defoliation

As ryegrass is a ‘3-leaf’ plant (Section 2.3.2.1), grazing delayed after the three leaf stage will lower the quality of the herbage through inclusion of senesced material and result in wastage (Fulkerson & Donaghy, 2001). Accordingly, grazing at the three-leaf stage is often practised. However, under conditions of rapid growth (i.e. sufficient moisture and nitrogen) pasture may reach a high mass of 2-2.2 t DM/ha at the two-leaf stage, although Fulkerson and Donaghy (2001) suggest that energy reserves may be low due to the leaf regrowth stage resulting in lower stubble water soluble carbohydrates (WSC). Fulkerson and Slack (1994), for example, recorded an increase in stubble WSC in perennial ryegrass within the regrowth cycle, with WSC increasing from 4-22% DM between the ‘1-leaf’ and ‘4-leaf’ stages.

Korte et al. (1982, 1984) identified that the timing and intensity of grazing affected perennial ryegrass regrowth and development. Hard grazing to a residual LAI of <0.9 encouraged a higher proportion of
active leafy growth compared with a laxly grazed pasture (LAI of 0.9-3), which had more dead and stem material. Similarly, when the pasture was grazed during early stem elongation a higher proportion of leaf accumulated than stem compared with grazing after 30% inflorescence emergence. Brougham (1956) also found that harder grazing led to a higher proportion of leafy growth but that 95% canopy cover was only achieved after 24 days compared with 12-16 days under a more lax grazing regime. Accordingly, when defoliated to a lower LAI it takes longer for the canopy to regain full photosynthetic capacity, and re-growth can be suppressed if the pasture is grazed too early, i.e. before the two-leaf stage (Fulkerson & Donaghy, 2001).

When related to pasture height, Fulkerson and Donaghy (2001) identify defoliation to ~50 mm will optimise ryegrass growth and persistence. Harsher defoliation practices will remove necessary WSC, which the pasture relies on to grow new shoots and regain photosynthetic capacity. Accordingly, severe defoliation reduces the regrowth and persistence of the pasture. More lax defoliation practices increase leaf senescence and reduce tillering rates, which ultimately lead to reduced herbage yields. In terms of the residual biomass, perennial ryegrass/white clover pastures in New Zealand are typically grazed to a residual of 800–1600 kg DM/ha to maintain pasture quality and encourage rapid canopy closure (Snow & White, 2013).

Potential evapotranspiration models include assumptions regarding the pasture, including full canopy closure, that it is of a uniform (clipped) height, well-watered, and well-fertilised (Section 2.4.2). However, these do not reflect the changes that occur under a grazed scenario, whereby the pasture height is regularly defoliated to below full canopy cover, and grazing does not occur evenly (Weeda, 1967).

2.3.2.6 Pasture growth modelling

There are a number of existing models used in the simulation of pasture growth, including DairyMod and EcoMod (Johnson et al., 2008), GrassGro (Clark et al., 2000), SGS (Sustainable Grazing Systems) (Johnson et al., 2003) and APSIM (Agricultural Production Systems Simulator) (Keating et al., 2003).

Both APSIM (Brown et al., 2010; Li et al., 2011; Moot et al., 2014; Snow & White, 2013; White & Snow, 2012) and DairyMod (Chapman et al., 2009; Cichota et al., 2008; Cullen et al., 2008; White et al., 2008) have been widely tested within New Zealand. However, DairyMod has been developed as a multi-paddock, biophysical simulation model specifically for dairy systems with a well developed pasture module, that encompasses the whole soil-plant-water system and is well published in New Zealand. Accordingly, DairyMod has been used in this research to simulate pasture growth and soil water flow processes (Section 2.3.3.4). Furthermore, the pasture model within APSIM (AgPasture) is an adaption of the pasture model from EcoMod and DairyMod (White & Snow, 2012).
**DairyMod**

DairyMod (version 5.3.13) is a biophysical pasture simulation model and includes modules for pasture growth and utilisation by grazing animals, animal physiology including animal production, water and nutrient dynamics, as well as a range of options for pasture management, irrigation and fertilizer application (Johnson *et al.*, 2008). The underlying processes within DairyMod have a common underlying structure to those in the EcoMod and the SGS pasture models. However, the models have differing livestock and management systems customised for different industries (i.e. DairyMod for dairy, SGS for sheep and beef and EcoMod for dairy, sheep, beef and deer systems). Within DairyMod, both mechanistic and empirical relationships are used (Johnson, 2013a).

**General**

The pasture growth module includes calculations of light interception and photosynthesis, growth and maintenance respiration, nutrient uptake and nitrogen fixation, partitioning of new growth into the various plant parts, development, tissue turnover and senescence, and the influence of atmospheric CO$_2$ on growth (Johnson, 2013a). The model allows up to five pasture species in any simulation, which can be annual or perennial, C$_3$ or C$_4$, as well as legumes, for each of which default parameter settings are given.

In general, pasture growth is calculated firstly by determining the daily transpiration rate and the effect of water stress (Johnson, 2013a). Daily photosynthesis is then calculated in response to light, temperature, atmospheric CO$_2$ concentration, canopy architecture, available water, and leaf nitrogen status. Potential nutrient uptake is described in relation to root distribution and soil nutrient status and the plant mass flux is calculated, incorporating tissue turnover, senescence, shoot and root growth.

**Photosynthesis**

A detailed analysis of the canopy photosynthesis model component is given by Johnson *et al.* (2010). Daily photosynthesis is calculated according to a number of steps. To summarise, the instantaneous rate of leaf gross photosynthesis is defined in response to photosynthetic photon flux (PPF), the mean daily temperature, atmospheric CO$_2$ and leaf N, followed by light interception and attenuation through the canopy, which includes direct and diffuse PPF components. These are integrated through the canopy to get canopy instantaneous gross photosynthesis and through the day to get daily canopy gross photosynthesis. Growth and maintenance respiration are then calculated and combined with the gross photosynthesis to get daily net photosynthesis. This represents the net carbon assimilation by the canopy (Johnson, 2013a).
Calculations of the daily photosynthetic rate are central to DairyMod as this provides the carbon source for the whole system. The source of energy for photosynthesis is the visible component of solar radiation, expressed as PAR or PPF.

The influence of temperature, CO\(_2\) and nitrogen level on leaf gross photosynthesis (\(P_\ell\)) (Equation 2.6) is dominated by the effect on the parameter \(P_m\) (Equation 2.7), being the rate of single leaf gross photosynthesis at saturating PPF. \(P_m\) increases from zero as the temperature increases from a specified minimum (Johnson et al., 2010). At some point \(P_m\) reaches an optimum temperature after which there is no further increase in \(P_m\). The optimum temperature increases due to a fall in respiration, but as temperature continues to rise, \(P_m\) declines for \(C_3\) species, also due to an increase in photorespiration. Increases in \(P_m\) occur in response to increases in protein concentration, or increases in the nitrogen content of the pasture. Protein concentration is used by the model instead of leaf nitrogen, as leaf N is often expressed as N per unit leaf area or N per unit plant mass, and is related to protein concentration through the specific leaf area (leaf mass per unit area) (Johnson et al., 2010). The equations for \(P_\ell\) and \(P_m\) are as follows:

\[
P_\ell = \frac{1}{2\xi}[\alpha I_\ell + P_m - \{(\alpha I_\ell + P_m)^2 - 4\xi\alpha I_\ell P_m\}^{1/2}]
\]

Equation 2.6

\[
P_m = P_{m,ref} f_C(C) f_{P_m,TC}(T, C) f_{P_m,N}(N)
\]

Equation 2.7

where \(\alpha\) is the photosynthetic efficiency, \(I_\ell\) defines the cumulative leaf area index through the depth of the canopy, \(\xi\) is a (constant) curvature parameter, \(I_\ell\) is the total PPF incident on leaves within the canopy (\(\mu\)mol photons/m\(^2\)/s), \(P_{m,ref}\) is a reference value for \(P_m\) (16 \(\mu\)mol/mol/m\(^2\) leaf for \(C_3\) species), and is the value of \(P_m\) at the reference temperature of 20\(^\circ\)C, \(f_c(C)\) is a CO\(_2\) response function, \(C\) is the actual atmospheric CO\(_2\) concentration, \(T\) is the mean daily temperature (\(^\circ\)C), \(f_{P_m,TC}\) is a combined response to temperature and CO\(_2\), \(f_{P_m,N}\) is the response to protein concentration as related to nitrogen (N), \(f_N\) kg N/kg C.

The temperature response of \(P_m\) is defined in terms of the minimum (\(T_{mn}\)), optimum (\(T_{opt}\)) and maximum (\(T_{mx}\)) temperatures, as follows:

\[
f_T(T) = \begin{cases} 
0, & T < T_{mn} \\
\frac{(T-T_{mn})^q}{(T_{ref}-T_{mn})^q}, & T_{mn} < T < T_{mx} \\
0, & T > T_{mx}
\end{cases}
\]

Equation 2.8

where \(q\) is a curvature parameter with a default value of 2 for perennial ryegrass and \(T_{ref}\) is a reference temperature so that:

\[
f_T(T_{ref}) = 1
\]

Equation 2.9

and \(T_{mx}\) is given by:
\[ T_{mx} = \frac{(1+q)T_{opt} - T_{mn}}{q} \]  \hspace{1cm} 2.10

Accordingly, the function takes its maximum value at \( T_{opt} \) and is zero outside of the range \( T_{mn} \) to \( T_{mx} \).

The optimum temperature for photosynthesis is seen to increase in response to atmospheric CO\(_2\) concentration and so the combined T and C function and function \( f_{Pm,TC}(T, C) \), uses Equation 2.8, but with \( T_{opt} \) defined:

\[ T_{opt, Pm} = T_{opt, Pm,amb} + \gamma_P f_C(C) - 1 \]  \hspace{1cm} 2.11

where \( \gamma_P \) has a default value of 10°C. Default values are given for C\(_3\) species for \( T_{ref} \) (20°C), \( T_{mn} \) (3°C) and \( T_{opt} \) (23°C).

Photosynthetic efficiency (\( \alpha \)) also depends on temperature, CO\(_2\) and N, as follows:

\[ \alpha = \alpha_{amb, 15} f_{\alpha, C}(C) f_{\alpha, TC}(T, C) f_{\alpha, N}(f_N) \]  \hspace{1cm} 2.12

where \( \alpha_{amb, 15} \) mol CO\(_2\)/mol photons is the value of \( \alpha \) at ambient CO\(_2\) concentration and 15°C, with a default value of 50 mmol CO\(_2\)/mol photons, \( f_{\alpha, C} \) represents the direct influence of C on \( \alpha \) and \( f_{\alpha, TC} \) defines the temperature response on \( \alpha \) and the influence of C, and \( f_{\alpha, N}(f_N) \) defines the protein response for \( \alpha \).

The rate of instantaneous gross canopy photosynthesis (\( P_g \) \( \mu \)mol CO\(_2\)/m\(^2\) ground/s) is calculated by summing the leaf photosynthetic rate over all leaves in the canopy, as follows, where LAI is the total canopy leaf area index:

\[ P_g = \int_{0}^{LAI} P_\ell(I_\ell) d_\ell \]  \hspace{1cm} 2.13

Daily canopy gross photosynthesis is given by the integral of \( P_g \) throughout the day.

Daily canopy maintenance respiration (\( R_{m, day} \)), primarily related to the resynthesis of degraded proteins, is strongly temperature dependent. Growth respiration (\( R_g \)) assumes that one unit of substrate that is utilised for growth results in Y units (kg) of structural material and (1-Y) units (kg) of respiration, where Y is the growth efficiency. Maintenance and growth respiration are represented in the model as follows:

\[ R_{m, day} = m_{ref} f_m(T) \frac{f_N}{f_{N, ref}} W \]  \hspace{1cm} 2.14

\[ R_g = \frac{1-Y}{Y} g \]  \hspace{1cm} 2.15

Where \( m_{ref} \) is the maintenance coefficient at the reference temperature and N content with a default value of 0.025/d, \( f_m(T) \) is a maintenance temperature response function, W is shoot mass (kg C/m\(^2\)), \( f_N \) the canopy N concentration (kg N/kg C), \( f_{N, ref} \) the reference N concentration, and g is growth (kg C/m\(^2\)/d).

The daily canopy gross photosynthesis and respiration are combined in the model to give the daily carbon fixation, or net growth rate (\( G \)) where \( R_N \) is the respiratory cost of N acquisition, as:
Temperature stress parameters have been included in DairyMod to manage maximum and minimum daily temperature extremes on photosynthesis, for example, where winter daytime temperatures may be suitable for growth but low night temperatures may prevent growth occurring (Johnson et al., 2008). Temperature stress has been separated into high and low temperature stress functions, each of which include an initial or minimum stress \((T_{mn,high}, T_{mn,low})\), a maximum stress \((T_{mx,high}, T_{mx,low})\) and a critical temperature sum for recovery from high and low temperature stress \((T_{sum,high}, T_{sum,low})\). The initial stress represents the temperatures above or below which high and low temperature stress will occur, and the maximum stress the temperatures above or below which temperature stress is maximal, respectively. For example, if on day \(i\), \(T_{mn}<T_{mn,high}\), then the temperature stress coefficient is calculated as:

\[
\xi_{T,low,i} = \begin{cases} 
\frac{T_{mn}-T_{mn,low}}{T_{mn,high}-T_{mn,low}}, & T_{mn} > T_{mn,low} \\
0, & T_{mn} \leq T_{mn,low}
\end{cases}
\]

and ranges between zero and one from \(T_{mn,low}\) to \(T_{mn,high}\). Conversely, if \(T_{mx}\geq T_{mx,high}\), then

\[
\xi_{T,low,i} = \frac{T_{mean}}{T_{sum,low}}
\]

It is important to note that the treatment of low and high temperature stresses on photosynthesis is completely empirical, although it is considered to capture the influence of temperature extremes and subsequent recovery (Johnson, 2013a).

Default values are given for \(C_3\) species for \(T_{mn,low}(0^\circ C), T_{mn,high}(5^\circ C), T_{sum,low}(100^\circ C), T_{mx,low}(30^\circ C), T_{mx,high}(35^\circ C)\) and \(T_{sum,high}(100^\circ C)\). However, by default, low and high temperature stress functions are not implemented for \(C_3\) plants within the model.

**Transpiration, water stress and evaporation**

The potential transpiration rate \((T_{pot})\) is calculated within DairyMod assuming full ground cover according to the Penman-Monteith equation (Section 2.4.2.1). The actual transpiration demand \((T_{demand})\) is calculated according to the live ground cover \((f_g)\), where \(f_g\) is determined as the proportion of solar radiation that is intercepted, using the canopy extinction coefficient and leaf area as follows:

\[
T_{demand} = f_g \times T_{pot}
\]

The soil water status is used to determine the actual transpiration from the actual transpiration demand, using a model similar to that of Feddes et al. (1978) (Section 2.3.3.4). A growth limiting factor \(g_{water}\) is defined in relation to the available soil water as a function of wilting point \((\theta_{wp})\), the critical capacity \((\theta_c)\), field capacity \((\theta_d)\) and the saturated soil water content \((\theta_s)\). If \(g_{water}\) is one then there are no growth limitations, and at zero there is total limitation. \(\theta_d\) represents the point, below which
Transpiration is reduced, and is therefore referred to as the transpiration stress function. As illustrated in Figure 2.5, below \( \theta_{wp} \) plants cannot abstract water, between \( \theta_{wp} \) and \( \theta_L \), \( g_{water} \) increases from 0-1, as was also illustrated by Figure 2.2. Between the \( \theta_{FC} \) and \( \theta_s \), \( g_{water} \) may again decline due to water logging effects. Where there is no limitation to water uptake from any layer, then transpiration is determined according to the relative root distribution. Compensated water uptake for water limitations in dry layers by others that have abundant water is accounted for within the model by running the transpiration functions three times, or until the demand is satisfied.

**Figure 2.5** Schematic representation of the influence of limiting soil water content on transpiration. Redrawn from Johnson (2013a). ‘\( g_{water} \)’ is the growth limiting factor, \( \theta_{wp} \), \( \theta_L \), \( \theta_{FC} \) and \( \theta_s \) are the soil water contents at the wilting point, the recharge point, field capacity and saturation.

The potential evaporation (\( E_{pot} \)) of water sitting on the leaves, litter or soil is addressed in a similar way as transpiration (i.e. using the Penman-Monteith equation (Section 2.4.2.1)), except that the resistance to water flow through the leaf stomata is removed, and therefore is comparable to the method employed by Ritchie (1972).

Evaporation from the canopy can only occur if there is any freestanding water on the canopy, and any water, if available, will evaporate at the potential rate. Similarly, if there is any water held in the litter then it too is available for evaporation. However, the evaporative demand is attenuated in relation to canopy cover.

Soil evaporation, being the flux of water from the soil to the atmosphere, occurs in response to the evaporative demand, ground cover and soil water content. The potential to evaporate from the soil declines with soil depth. The actual water available for evaporation in each soil layer (\( H_{evap,\ell} \)) and the potential soil evaporation (\( E_{pot,soil} \)) are determined as follows:

\[
H_{evap,\ell} = \mu_{\ell}(\theta_{\ell} - \theta_{FC,\ell})\delta z_{\ell} \tag{2.20}
\]

\[
E_{pot,soil} = (1 - f_g)(1 - f_{g,litter})E_{pot} \tag{2.21}
\]
where \( \ell \) is the soil layer, \( \mu_\ell \) the function describing the potential to evaporate based on depth, \( \theta \) the actual volumetric water content, \( \theta_{\text{fc}} \) the volumetric water content at field capacity, \( \delta z_\ell \) the layer thickness (m) and \( f_{g,litter} \) is the ground cover due to the presence of litter. In the model, the first four soil layers (from the surface) are set at 50 mm each, and then subsequent layers are 100 mm.

The model works through the soil layers, starting at the top and removes water from each according to Equation 2.20 and up to the limit given by Equation 2.21.

**Soil water infiltration**

The water module accounts for rainfall and irrigation inputs that can be intercepted by the canopy, surface litter or soil. The required hydraulic soil parameters are saturated hydraulic conductivity (\( K_{\text{sat}} \)), bulk density, field capacity or drained upper limit, wilting point and air-dry water content.

DairyMod employs a capacitance model to simulate water flow \( q \) (Johnson *et al.*, 2008), as given by:

\[
q = K_{\text{sat}} \left( \frac{\theta}{\theta_s} \right)^\sigma \tag{2.22}
\]

\[
\sigma = \frac{\ln (q_{\text{fc}} / K_{\text{sat}})}{\ln (\theta_{\text{fc}} / \theta_s)} \tag{2.23}
\]

where \( \sigma \) is a flux coefficient, \( \theta_{\text{fc}} \) and \( \theta_s \) are the volumetric water contents at field capacity and saturation, and \( q_{\text{fc}} \) the flow rate at field capacity, assumed within DairyMod to be 0.1 mm/d. Using this approach, only water in excess of the drainage point can move, and all movement is downwards. The flux decreases as the available water for movement declines, as controlled by \( \sigma \), which in turn is derived from the water holding capacity of the soil. The method is applied by dividing the soil into layers, the number and thicknesses for which are determined by the model. A sub-daily time-step is then calculated by the model, preventing water movement from a given layer exceeding that which is available.

Accordingly, this approach compares with a tipping-bucket model approach (Section 2.3.3.4), but includes the use of hydraulic conductivity and finely separates the soil profile into a number of layers (Johnson *et al.*, 2008).

**Irrigation Scheduling**

The irrigation options within the model allow the user to select from a range of irrigation managements or rules. The rules allow irrigation to be applied in response to plant water status, soil water deficit, rainfall deficit (difference between accumulated potential evapotranspiration and rainfall), as well as regular intervals or specified dates. For each strategy, the amount of water, or target soil water content can be prescribed, as well as rules for the timing of irrigation within the day and throughout the year (Johnson *et al.*, 2008).
Model performance

Cullen et al. (2008) tested the ability of DairyMod to simulate net herbage accumulation rates of ryegrass-based pastures in Australia and New Zealand. For the simulations, Cullen et al. (2008) adjusted the minimum and optimum $P_m$ default values for perennial ryegrass from 3 and 23°C to 5 and 20°C for dryland, winter-dormant pastures and to 3.5 and 20°C for irrigated and dryland winter-active pastures (Table 2.1). The high and low extreme temperature responses were activated for the winter-dormant ryegrass, as were the high-temperature responses for the dryland winter-active pastures. The $P_m$ temperature adjustments were tested against cut trial datasets using a ‘trial and error’ approach and showed the best fit applied to other datasets without further adjustment. Inactivating the extreme high-temperature responses when the pasture was irrigated was to moderate the high-temperature growth restriction under irrigated conditions. Overall, close agreement was achieved between the observed and simulated data with herbage mass differences of 0.4-30.3% for ryegrass-based pastures under varying environmental and management conditions. For fertilised plots (with or without irrigation), simulated yields were between 0.4-15.9% of those measured, while differences of up to 30.3% were predicted for unfertilised pastures. The effect of adjusting the temperature responses was highlighted in a comparison between the winter-dormant and winter-active pastures, whereby the net yield accumulation of the winter-active pastures was 20% higher annually due to the reduced temperature growth restrictions. Some limitations in the model were, however, highlighted by Cullen et al. (2008). Firstly, the model did not incorporate plant phenological development, so does not explicitly simulate the physiological changes that occur with reproductive development, including accelerated growth rate and increased proportion of stem material. This may be of particular significance to modelled spring herbage accumulation. Secondly, the model did not simulate perennial ryegrass plant persistence so declining plant densities and associated reductions in pasture growth rate cannot be captured. However, it was highlighted that this is of more relevance to sub-tropical environments rather than the temperate Canterbury climate. Lastly, no account is given within DairyMod to plant carbohydrate reserves, which may lead to discrepancies between modelled and observed data.

White et al. (2008) used EcoMod, which uses the same pasture growth module as DairyMod, to test how well the model simulated the changes in growth rate and plant composition of dryland and irrigated pasture production in a temperate climate through comparison with a long-term (1966–2003) data set measured in New Zealand. In general, close agreement was achieved between the measured and modelled total annual and monthly growth rates. This was particularly so following modifications to some of the parameters of plant growth to more accurately represent the characteristics of dominant species present under dryland and irrigated pastures. For example, where nitrogen was non-limiting, annual yields were able to be predicted within 3 and 2.5% of those measured under dryland
and irrigated conditions, respectively. Modifications made were to the model default photosynthetic minimum and optimum temperature responses, the high and low temperature extremes, and the model default rooting depths of 400 mm and 300 mm for perennial ryegrass and white clover, respectively, under both dryland and irrigated conditions. The modifications made are summarised in Table 2.1.

### Table 2.1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Default</th>
<th>White et al. (2008)</th>
<th>Cullen et al. (2008)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>RG</td>
<td>WC</td>
<td>Dryland RG</td>
</tr>
<tr>
<td>Photosynthesis</td>
<td>Minimum (°C)</td>
<td>3 3</td>
<td>3 3</td>
<td>5 3.5 3.5</td>
</tr>
<tr>
<td></td>
<td>Optimum (°C)</td>
<td>23 23</td>
<td>20 20</td>
<td>20 20 20</td>
</tr>
<tr>
<td>Low temperature stress</td>
<td>Implement</td>
<td>False False True True True</td>
<td>True False False</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Initial (°C)</td>
<td>- -</td>
<td>0 1</td>
<td>Not specified - -</td>
</tr>
<tr>
<td></td>
<td>Full (°C)</td>
<td>- -</td>
<td>-3 -3</td>
<td>- -</td>
</tr>
<tr>
<td></td>
<td>Recovery (°C sum)</td>
<td>- -</td>
<td>30 30</td>
<td>- -</td>
</tr>
<tr>
<td>High temperature stress</td>
<td>Implement</td>
<td>False False True True True</td>
<td>True True False</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Initial (°C)</td>
<td>- -</td>
<td>25 26</td>
<td>- -</td>
</tr>
<tr>
<td></td>
<td>Full (°C)</td>
<td>- -</td>
<td>30 31</td>
<td>- -</td>
</tr>
<tr>
<td></td>
<td>Recovery (°C sum)</td>
<td>- -</td>
<td>50 30</td>
<td>- -</td>
</tr>
<tr>
<td>Roots</td>
<td>mm</td>
<td>400 300</td>
<td>300 400 400</td>
<td>-</td>
</tr>
</tbody>
</table>

On the basis that DairyMod had been used to represent pasture herbage accumulation rates with reasonable accuracy by Cullen et al. (2008) and White et al. (2008), Chapman et al. (2009) used DairyMod to estimate mean monthly herbage accumulation rates of annual or perennial ryegrass-based pastures in 35 years (1972–2006) for three sites in New Zealand, including Winchmore in Canterbury. The aim of the study was to evaluate whether or not a probabilistic approach to the analysis of pasture growth could provide useful information to support decision-making. It was found that model predictions can provide an important source of information, for example, to support feed budgeting and feeding decisions, but should be coupled with published data, direct experience, and other relevant information to analyse risk.

### 2.3.3 Soil influences on evapotranspiration

Soil type and the hydraulic properties of a soil have the potential to influence spatial variations in evapotranspiration. The influence of soil relates to the water storage capacity of a soil (Allen et al., 1998; Meyer & Mateos, 1990). For example, each of the experiment sites included in this research are characterised by differing soil types, each with individual soil hydraulic characteristics and therefore soil water holding capacities (Sections 3.2.2 and 5.2.2). The water storage capacity of a soil affects the
time it takes for it to dry out. Lighter soils, which are characterised by a higher (≥50%) sand component (e.g. sandy loam) have a tendency to dry out faster than heavier soils (≥35% clay), reducing the amount of water available to the plant (Allen et al., 1998; McLaren & Cameron, 1996; Webb & Lilburne, 2011).

Across the Canterbury Plains, soil types vary from shallow and light to deep and heavy. Across the experiment sites, soil types vary from a deep (>1m) Wakanui silt loam (Udic Ustochrept (U.S.D.A., 1984)) with a total water holding capacity of 150-200 mm in the upper 500 mm soil profile (Webb, 1995; Webb et al., 2000) to a shallow Darnley silt loam (Inceptic Hapludalf (U.S.D.A., 1984)) with a water holding capacity of ~145 mm in the upper 500 mm soil profile (Dr Sam Carrick, pers. comm., 23 May 2012).

In addition to influencing the amount of water available to the plant, soils characterised by larger storage capacities are able to make more effective use of water inputs of rainfall (and irrigation) and therefore minimise potential drainage losses.

Drainage is a key input to the water balance equation (Equation 2.1), and where all other variables are known, drainage can be estimated. Previous lysimeter studies in Canterbury have identified annual groundwater recharge under irrigation to be in the range of 25-52% (Thorpe & Scott, 1999; White et al., 2003). Other lysimeter studies across New Zealand also indicate groundwater recharge to be on average 35-54% of total inputs from rainfall and irrigation (Annett, 1949; Barkle et al., 1998). Under pastoral dryland managements at Winchmore, Canterbury, recharge has been reported to be 8-36% (Thorpe & Scott, 1999).

Within the literature, an appreciation of drainage variability at a particular site or within a soil type due to spatial non-uniformity can be obtained. Wang et al. (2012), for example, presented drainage data from a lysimeter study for three soil types found within Canterbury and Southland, including a Lismore soil. Total average drainage, with error bars, was given for each site, from which coefficients of variation (CV) of 7-19% were estimated for each soil type. An average CV of 27% was determined from lysimeter drainage data presented by Close and Woods (1986) from a series of lysimeter sites across five North Canterbury soils. Much lower variability was observed by Barkle et al. (1998) and McLeod (Malcolm McLeod, Landcare Research, pers. comm., 09 Jul. 2013), which provide some indication of achievable CV values under some conditions. Barkle et al. (1998), for example, presented drainage data from three sets of three lysimeters containing undisturbed Te Kowhai soil monoliths (600 x 1200 mm), growing ryegrass, for which CV values ranged between 0.3-2.8% for five years of data. Similarly, CV values of 2.79-3.47% were identified by McLeod (Malcolm McLeod, Landcare Research, pers. comm., 09 Jul. 2013) based on large (1000 mm diameter) lysimeters growing lucerne (Medicago sativa L.).
2.3.3.1 Water quality implications

While this research is not water quality focused, excess drainage carries within it implications for freshwater quality, and therefore has been briefly covered.

It is well documented throughout the literature that irrigation in excess of the soil water holding capacity can increase the potential for nutrient leaching losses to groundwater (Hu et al., 2010; Lilburne et al., 2010; Maharjan et al., 2014; Meisinger & Delgado, 2002; Moreno et al., 1996; Zemansky et al., 2006). Lilburne et al. (2010) reported increased nitrate-N leaching concentrations and volumes of nitrate leached with irrigation from extremely light to heavy soils across Canterbury. Accordingly, where irrigation is applied so as to minimise drainage, the potential for nitrate leaching is reduced.

Inorganic forms of nitrogen (N) and phosphorus (P), primarily as nitrate-N and dissolved reactive phosphorus (DRP) have been identified as the greatest threat to freshwater quality, as they promote biological growth of periphyton and macrophytes to nuisance levels (Dymond et al., 2013).

Within Canterbury, large areas of high-nitrate leaching have been identified, driven by mean annual rainfall and stocking density. Over the past 20 years, dairy cattle numbers have increased 10-fold which has led to a doubling of nitrate-N leaching losses from 10 000 to 20 000 t nitrate-N/y within the region (Dymond et al., 2013).

2.3.3.2 Soil water infiltration

The infiltration rate refers to the rate at which water can enter the soil surface, and therefore has implications for the rate at which the soil profile will recharge with water and the potential for the redistribution of water at the soil surface (Hillel, 1998; McLaren & Cameron, 1996). Where the application intensity of water to the soil surface is in excess of the infiltration rate, water will accumulate at the surface or flow over it. The non-uniformity of soils (both in texture and initial wetness) can lead to non-uniform infiltration and spatial redistribution of otherwise evenly applied water (Hillel, 1998).

Surface redistribution of water and uneven wetting of the soil is common on Canterbury soils, often related to fine micro topographic variations and channelling of water by the pasture (Clothier & Heiler, 1983; Kanchanasut & Scotter, 1982; Webb, 1989). Wallis et al. (1991) reported water repellency at field moisture conditions was the norm for a wide range of soils in Canterbury and across New Zealand, increasing the likelihood of run-off. Webb (1989) found that substantial redistribution of water can occur under relatively low intensity rainfall.

Infiltration rates reported in the literature for soils included in the current research have been detailed. According to Hillel (1998), steady infiltration rates, which are approximately equal to the field saturated hydraulic conductivity of the surface soil, vary from <1 mm/h for clayey soils to >20mm/h for sandy soils. For loams and silty soils, the steady infiltration rate ranges from about 5-20 mm/h.
Similarly, the irrigation Code of Practice (INZ, 2007) recommends irrigation is applied at up to 10 mm/h on silt loam soils to minimise surface redistribution of water, although for shorter watering periods (i.e. 5-100 minutes), up to 40 mm/h may be appropriate. These values compare with the 20 mm/h infiltration rate from a ‘wet’ Templeton silt loam reported by Quin and Forsythe (1978). Jiang (2008) and Silva et al. (2000) measured steady infiltration rates of 1.06-2.74 and 0.30-0.90 mm/h under 0.4 kPa and 0.5 kPa suction, respectively, and 0.72-27.4 mm/h under field saturated conditions (i.e. 0 kPa suction). The measured infiltration rates above 20 mm/h were considered to be reflective of higher macropore flow (Jiang, 2008). Jiang (2008) also reported initial infiltration into a dry Templeton soil, where the suction gradients were high, to be up to 250 mm/h. However, these were subject to rapid decline as the profile wetted.

Powers (2012) reported saturated infiltration rates of Lismore soils to range from 54-243 mm/h. Findings from Jiang (2008) and Silva et al. (2000), however, indicated saturated infiltration rates are about an order of magnitude higher than those at 0.4-0.5 kPa suction. Transforming the saturated rates measured by Powers (2012) according to this measure gives steady infiltration rates of 5.4-24.3, in general agreement with the 5-20 mm/h suggested by Hillel (1998) for loams and silty soils, and with the 10 mm/h irrigation application rate recommended by Irrigation New Zealand (INZ, 2007). Stoker (1982) found preferential water movement through the soil occurred in Lismore soils when water was applied to a dry soil at rates of 8-600 mm/h. Visible ponding was observed for all rates, except when water was applied at 8 mm/hr. When irrigation was applied at 40 mm/h with a moving boom irrigator, ponding occurred initially although the water had soaked into the profile prior to the next pass of the boom. As the soil moisture increased, more permanent ponding occurred at the surface.

Surface (initial and steady state) infiltration rates of water into Wakanui silt loam soils have been reported to differ within the Lincoln area depending on management practices. Hermawan (1990), for example, reported an initial infiltration rate of ~360 mm/h reducing to a steady state infiltration rate of 15.6 mm/h for a ryegrass under permanent pasture. Gibbs (1986) found infiltration rates to range between ~110 and 390 mm/h for a ploughed ryegrass pasture and 75 and 175 mm/h for a direct drilled ryegrass pasture over a two-year experiment period. Similarly Lance (1987) reported infiltration rates to vary under ryegrass-based pastures from 2.2-12 mm/h with heavy stocking, 26-220 with light stocking, 150-240 mm/h for a direct drilled ryegrass pasture and 170-420 mm/h for a ploughed ryegrass pasture. McLay (1989) reported decreasing rates of 10.2, 5.8 and 3.3 mm/h with increased irrigation water application.

2.3.3.3 Soil moisture measurement

Obtaining accurate measurements of the soil moisture is fundamental to research focused on quantifying evapotranspiration, whereby changes in soil moisture storage are a key input to the water balance equation (Equation 2.1).
Neutron probes provide an accurate, repeatable, non-destructive method of soil moisture measurement (Jensen, 1983). They contain a radioactive source of fast neutrons, and a detector of slow neutrons. Fast neutrons are emitted into the soil and undergo thermalisation. The concentration of the thermalised neutrons is directly proportional to the concentration of hydrogen in the soil, and therefore the volume of water (Hillel, 1998; Thomas, 1993). However, near surface measurements (i.e. 0-200 mm) of soil moisture using neutron probes can be unreliable due to neutron escape through the soil surface, distorting the reading of returning slow neutrons (Hillel, 1998; Jensen, 1983). Furthermore, steep soil moisture gradients and rapid changes with time in the near-surface water content (i.e. to top 50-100 mm) can cause errors in the near-surface readings (Painter, 1976). Thus, to determine the volumetric water content of the upper 200 mm of the soil profile Time Domain Reflectometry (TDR) or Time Domain Transmission (TDT) sensors can be used.

TDT and TDR sensors calculate the soil moisture content from the soil permittivity, determined from the travel time of an electromagnetic wave transmitted along a waveguide through the soil (Blonquist Jr et al., 2006). According to Blonquist Jr et al. (2005), TDT sensors are characterised by relatively high accuracy in their determination of soil permittivity, can rapidly take repeated measurements in-situ, and provide instantaneous measurements.

Throughout the literature, the frequency of soil moisture measurements ranges from 7-10 days during the growing season, with readings taken every 100-150 mm through the profile (Mills et al., 2009; Moot et al., 2008; Scotter et al., 1979). In this study a combination of TDR and neutron probe methods were used to measure the volumetric soil water content. Measurements were taken every 100 mm at approximately weekly intervals over the growing season.

2.3.3.4 Soil water flow modelling

While understanding drainage of water from the soil, redistribution of water over the soil surface and soil moisture within the soil is fundamental to water balance closure (Equation 2.1), often measurement of these is not practical. In such situations, computer simulation models can be used.

Many models have been developed and tested to simulate water flow processes, which vary in complexity, in their approach, and their application. Addiscott and Wagenet (1985) provide a summary of various modelling approaches; differentiating deterministic from stochastic models, mechanistic from functional models, and models with a research focus from those developed as a guide for improving the management of soil water. This distinction was also drawn on by Avogadro and Ragaini (1993) in their review of various flow models.

In its simplest form, soil-water flow can be simulated using a tipping bucket model, which takes a deterministic, functional approach to soil water flow. These models are based on the underlying assumption that the soil root zone is like a bucket or container in which the water content fluctuates.
Essentially, the ‘bucket’ is filled by precipitation and irrigation and emptied by evaporation and outflow (i.e. runoff or drainage). When the bucket representing the soil root zone is full the excess inflows leave as drainage (or surface runoff) (Ranatunga et al., 2008). These models can assume either single layer homogenous soils or multilayer soils for which the soil and water characteristics of each layer can vary. The DairyMod model, for example, uses a multilayer tipping bucket approach to simulate soil water flow (Section 2.3.2.6). Ranatunga et al. (2008) illustrate the bucket concept, as shown in Figure 2.6.

![Figure 2.6 Schematic diagram of basic processes employed in the single layer (a) and multi-layer tipping bucket approach to water balance modelling. Adapted from Ranatunga et al. (2008).](image)

Advances in computer technology and understanding of the dynamic soil-water-plant relations have led to advances in numerical soil-water transport models, including (but not limited to): SPASMO (Soil-Plant-Atmosphere System Model) (Green, 2001; Green et al., 2004; Green et al., 2003); SWIM (Soil Water Infiltration and Movement) (Ross, 1990); HYDRUS (Šimůnek et al., 2013) and DairyMod (Johnson et al., 2008). Each of these models are mechanistic in their approach and allow for complex simulation of water and solute transport and plant uptake, except for DairyMod, which is a biophysical pasture simulation model and which incorporates a soil-water flow component, determined from a range of empirical to mechanistic relationships (Section 2.3.2.6).

Of the soil models developed and used, HYDRUS is the most widely adopted, and has been extensively and successfully used under New Zealand conditions in modelling water and solute flux transport through a range of soils (Cichota & Snow, 2009; Dann et al., 2010; Jiang et al., 2010; Mertens et al., 2005; Pang et al., 2008; Sarmah et al., 2006; Sarmah et al., 2005), in part owing to the open-source access to the HYDRUS-1D software package (HYDRUS). HYDRUS (version 4.16) has therefore been used in the current study. As DairyMod is used in the current study to simulate pasture growth (Section 2.3.2.6), it has also been used to simulate soil water flow, the results from which are compared with
the HYDRUS simulations. Within the literature, however, nothing could be found evaluating the ability of DairyMod to accurately simulate soil water flow.

HYDRUS

HYDRUS, developed by the U.S. Salinity Laboratory, is a finite element model used to simulate water flow, heat movement and solute transport in one-dimensional, variably saturated media (Šimůnek et al., 2013).

HYDRUS numerically solves for one-dimensional, uniform, unsaturated-saturated water flow using Richards’ equation (Equation 2.24), with the assumption that the air phase plays an insignificant role in the liquid flow process and that water flow due to thermal gradients can be neglected.

\[
\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x} \left[ K \left( \frac{\partial h}{\partial x} + \cos \alpha \right) \right] - S \tag{2.24}
\]

where \( h \) is the pressure head (mm), \( \theta \) the volumetric water content of the soil (mm\(^3\)/mm\(^3\)), \( t \) is time (d), \( x \) is the spatial coordinate (mm), \( S \) is the sink term (mm\(^3\)/mm\(^3\)/d), \( \alpha \) is the angle between the direction of flow and the vertical axis (i.e. 0° for vertical flow and 90° for horizontal flow or 0° < \( \alpha \) < 90° for inclined flow) and \( K \) is the unsaturated hydraulic conductivity function (mm/d) given by:

\[
K(h, x) = K_{\text{sat}}(x) K_{\text{rel}}(h, x) \tag{2.25}
\]

where \( K_{\text{rel}} \) is the relative hydraulic conductivity [-] and \( K_{\text{sat}} \) the saturated hydraulic conductivity (L/T).

Root water uptake

HYDRUS employs the Feddes et al. (1978) sink function (S) to determine the volume of water removed from a unit volume of soil per unit time due to plant water uptake. This function was expanded by Van Genuchten (1987) to include osmotic stress and accounts for non-uniform distribution of the potential water uptake rate over the root zone, as follows:

\[
S(h, h_\phi, x) = \alpha(h, h_\phi, x) b(x) T_{\text{pot}} \tag{2.26}
\]

where \( h_\phi \) is the osmotic head (mm). The root-water uptake water stress response function \( \alpha(h) \) is a prescribed dimensionless function of the soil water pressure head (0 ≤ \( \alpha \) ≤ 1), \( b(x) \) the normalised water uptake distribution function (mm\(^{-1}\)), describing spatial variation of the potential extraction term over the root zone and \( T_{\text{pot}} \) the potential transpiration rate (mm/d). As illustrated in Figure 2.7, water uptake is assumed to be zero close to saturation (\( h_1 \)) and where \( h<h_4 \) (the wilting point pressure head). Water uptake is considered optimal between pressure heads \( h_2 \) and \( h_3 \), whereas for pressure heads between \( h_3 \) and \( h_4 \) (or \( h_1 \) and \( h_2 \)), water uptake decreases (or increases) linearly with \( h \). \( T_{\text{pot}} \) is equal to the water uptake rate during periods of no water stress when \( \alpha(h)=1 \).
The ratio of actual to potential transpiration ($T_{\text{act}}/T_{\text{pot}}$) of the root uptake is defined by introduction of a water stress index ($\omega$). For fully compensated root-water uptake, a critical value of the water stress index ($\omega_c$) was also introduced, which represents a threshold value above which root water uptake reduced in stressed parts of the root zone is fully compensated by increased uptake from other parts.

**Evaporation and transpiration**

Evaporation ($E$) is computed as a water flux going out of the soil system, limited either by an atmospherically determined potential evaporation ($E_{\text{pot}}$), or by the rate of water that can be supplied to the soil surface (Kool et al., 2014; Šimůnek et al., 2013). Evaporation is defined as follows:

$$E = -K \frac{\partial h}{\partial x} - K \leq E_{\text{pot}} \quad \text{at} \quad x = L$$

and

$$h_A \leq h \leq h_s \quad \text{at} \quad x = L$$

where $h$ is the boundary pressure head, $h_A$ and $h_s$ are the minimum and maximum pressure head at the soil surface allowed under the prevailing soil conditions ($L$), respectively, $x$ is the spatial coordinate (positive upwards) and $L$ is the $x$-coordinate of the soil surface above a certain reference plane (depth of the soil profile, mm).

The actual transpiration is limited either by potential transpiration ($T_{\text{pot}}$) or the rate at which water can be transported to a pre-defined root zone (Kool et al., 2014; Šimůnek et al., 2013). Transpiration is defined as a function of root water uptake as follows:

$$T_{\text{act}} = \int_{L_R} S(h, h_{\phi}, x) \, dx = T_{\text{pot}} \int_{L_R} \alpha(h, h_{\phi}, x) \, b(x) \, dx$$

where $L_R$ is rooting depth (m), $S(h, h_{\phi}, x)$ is the sink term defined as the volume of water removed from a unit volume of soil per unit time due to plant water uptake and $\alpha(h, h_{\phi}, x)$ is the water stress response function from Equation 2.26.
T_{pot} and E_{pot} can be either predefined by the user or the potential evapotranspiration can be input along with either the Leaf Area Index (LAI) or surface fraction covered by plants for the model to separate into T_{pot} and E_{pot}. In the current study, potential daily evaporation and transpiration were separately estimated using the Shuttleworth-Wallace model (Section 2.4.2.4), which were then input directly to the model.

**The unsaturated soil hydraulic properties**

HYDRUS allows for the use of up to five varying analytical models for describing the unsaturated soil hydraulic properties, which comprise the van Genuchten (1980), Brooks and Corey (1966), and modifications of van Genuchten (1980) equations. The soil water retention, \( \theta(h) \), and hydraulic conductivity, \( K(h) \), functions according to Brooks and Corey (1966) are given by:

\[
S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \begin{cases} 
1, & 0 \geq \psi > \psi_e \\
\left(\frac{\psi}{\psi_e}\right)^{-1/b}, & \psi \leq \psi_e 
\end{cases}
\]

\[
K = K_{sat} S_e^{2/n+2} \quad 2.31
\]

Where \( S_e \) is the effective saturation, \( \theta_r \) and \( \theta_s \) are the residual and saturated water contents (mm³/mm³), respectively, \( \psi_e \) is the air entry water suction (kPa), \( n \) is a pore size distribution index and \( b \) is a fitting constant. The pore connectivity parameter \( l \) in the hydraulic conductivity function was estimated by Mualem (1976) to be about 0.5 on average for a wide range of soils.

The soil-hydraulic functions of van Genuchten (1980), who used the statistical pore-size distribution model of Mualem (1976) to obtain a predictive equation for the unsaturated hydraulic conductivity function in terms of soil water retention parameters, are given by:

\[
\theta(h) = \begin{cases} 
\theta_r - \frac{\theta_s - \theta_r}{[1 + (ah)^n]^m} h < 0 \\
\theta_s & h > 0
\end{cases} \quad 2.32
\]

\[
K(h) = K_{sat} S_e \left[1 - (1-S_e^{1/m})^m\right]^2 
\]

\[
m = 1 - 1/n, \quad n > 1 \quad 2.33
\]

Where \( S_e, \theta_r \) and \( \theta_s \) and \( l \) are equal to the parameters used in the Brooks and Corey (1966) model, and \( \alpha \) is the inverse of the air-entry value (1/cm).

Where the soil hydraulic properties \( \theta_r \) and \( \theta_s \), \( n \), \( \alpha \) and \( l \) are unknown, they can be estimated using either Rosetta Lite, version 1.1 (Rosetta) (Schaap et al., 2001) or the RETC package (version 6.02) (van Genuchten et al., 1991).

Rosetta, which has been coupled with HYDRUS, was independently developed by Marcel Schaap at the U.S. Salinity Laboratory (Schaap et al., 2001). Rosetta implements pedotransfer functions which predict
van Genuchten (1980) water retention parameters and the saturated hydraulic conductivity ($K_{sat}$) in a hierarchical manner from soil textural class information, the soil textural distribution, bulk density and one or two water retention points (Šimůnek et al., 2013).

Alternatively, RETC provides several options for describing or predicting the hydraulic properties of unsaturated soils, including the soil water retention curve and hydraulic conductivity (van Genuchten et al., 1991). These hydraulic properties are key parameters in any quantitative description of water flow into and through the unsaturated zone of soils. The program uses the van Genuchten (1980) and Brooks and Corey (1966) models to represent the soil water retention curve, and the theoretical pore-size distribution model of Mualem (1976) to predict the unsaturated hydraulic conductivity function from observed soil water retention data.

**Soil water storage**
The HYDRUS code performs water balance computations at prescribed times for preselected subregions of the flow domain (Šimůnek et al., 2013). The water balance information for each subregion consists of the actual volume of water, $V$, in that subregion, and the rate, $O$ [L/T], of inflow or outflow to or from the subregion. The variables $V$ and $O$ are evaluated in HYDRUS by means of:

\[ V = \sum_e \Delta x_i \frac{\theta_i + \theta_{i+1}}{2} \]  \hspace{1cm} 2.35

\[ O = \frac{V_{new} - V_{old}}{\Delta t} \]  \hspace{1cm} 2.36

where $\theta_i$ and $\theta_{i+1}$ are water contents evaluated at the corner nodes of element $e$, $\Delta x_i$ is the size of the element, and $V_{new}$ and $V_{old}$ are volumes of water in the subregion computed at the current and previous time levels, respectively. The summation in Equation 2.35 is taken over all elements, $e$, within the subregion.

**Irrigation scheduling**
HYDRUS allows irrigation to be triggered by the user through a user-specified pressure head at a prescribed depth or observation node, which once reached, irrigation is triggered. The user can specify a lag period between when the pressure head is reached and the time irrigation starts, and also the rate at which irrigation is applied and the duration for which it is applied (Šimůnek et al., 2013). One limitation of the scheduling component within HYDRUS-1D is the inability to set a minimum return interval. Another restriction is in regard to the trigger function, whereby irrigation is triggered based on the pressure head of a single point rather than the water content of the profile as a whole, or a set region. Consequently, an irrigation event may be triggered, but, if the movement of the water front through the profile is slow there will be a delay between when the irrigation is applied and when the water front reaches the observation node. Accordingly, the model has the potential to trigger another irrigation event, and therefore overwater the soil profile.
**Model performance**

As HYDRUS is a widely used software package for modelling unsaturated flow, there are a large number of examples of its applications throughout the literature.

Sansoulet et al. (2008), for example, used HYDRUS to simulate spatially distributed water fluxes in an Andisol soil under banana plants and found spatially distributed drainage fluxes were well reproduced. HYDRUS was used to simulate water flow and leaching of faecal coliforms and bromide through six undisturbed soil lysimeters under field conditions by Jiang et al. (2010). Both spray and flood irrigation practices were used. When the single-porosity flow model was applied, HYDRUS successfully simulated water flow under spray irrigation. For lysimeters under flood irrigation, however, a dual-porosity flow model had to be used to achieve agreement between predicted and observed water contents due to preferential flow paths becoming more significant. In the current research, all irrigation was via spray methods. Similarly, Close et al. (2003) found HYDRUS simulations of bromide and hexazinone concentrations in the groundwater gave a close fit to observed data from three monitoring wells following a large recharge pulse.

Kargas and Kerkides (2011) used HYDRUS in the calculation of the moisture profiles in a horizontal infiltration experiment, but found the calculated profiles moved faster than the experimental ones. The explanation given for this was that the faster advancement of the HYDRUS-1D moisture profiles might have been due to a violation of Darcy’s law where there were high hydraulic gradients at the very early stages of the infiltration phenomenon. Kumar (2002) identified that the Richards equation applies only to stable flow, which has the potential to result in the under-estimation of the velocity and depth of water/solute transport. Examples of instability or flow not accounted for by the Richards equation include abrupt and gradual increases in the hydraulic conductivity with depth, air compression ahead of the wetting front, water repellency of the solid phase, and preferential flow through non-capillary macropores.

### 2.4 Estimation of potential evapotranspiration

Estimation of PET (PET$_{c}$ or PET$_{o}$) is based on combination equations such as the empirical Penman-Monteith equation, or other derivatives or simplifications of it.

Numerous equations have been developed to estimate, with accuracy, PET using climatological data. Some of the developed methods include the use of crop coefficients or alternatively PET models such as the Penman-Monteith (PM) and FAO modified Penman-Monteith (PM$_{FAO}$), French and Legg (FL) Priestley-Taylor (PT), Blaney-Criddle (BC), Thornthwaite (Th), Hargreaves (Hg), dual crop-coefficient (DCC) and Shuttleworth-Wallace (SWW) methods (Allen et al., 1998; French & Legg, 1979; Jensen, 1973; Jensen et al., 1990; Shuttleworth & Wallace, 1985). Of these methods, the PM and PM$_{FAO}$
methods are recognised internationally as the standard for the definition and calculation of PETc and PETa, respectively, due to their ability to maintain a high level of accuracy under varying conditions (Allen et al., 1998). This is largely owing to their combination approach with the inclusion of solar radiation, air temperature, relative humidity, and wind speed variables compared with the PT method, which is radiation based, and the Th, BC, and Hg methods, which are all temperature based (Jensen, 1973; Jensen et al., 1990). Accordingly, the PT, Th, BC, and Hg methods provide a simpler estimation of PET compared with the PM model, and enable the estimation of PET when measured variables, such as humidity, wind speed, and radiation are unavailable. Nonetheless, such simplifications can lead to losses in accuracy, which has been the subject of numerous investigations (Doorenbos & Pruitt, 1975; Irmak et al., 2006; Jensen et al., 1990). However, Jamieson (1982) found the PT method provided more accurate estimates of PET than PM for a barley (Hordeum vulgare L.) crop grown in Canterbury, when calculated at 30-minute time steps. Crop coefficients are generally coupled with PETa estimates calculated using the PMrAD method and provide a simplified approach to estimating PETc. French and Legg (1979) provide an adaptation to the original Penman method (Penman, 1948). For a bare soil, PET is assumed equal to the potential soil surface evaporation (e.g. determined from neutron probe data). From 0-50% ground cover, PET is equal to 50% of the summed potential evaporation for bare soil and transpiration for a full cover canopy, and at a ground cover greater than 50%, PET is equal to the potential canopy transpiration. The DCC and SWW models are both, to some degree also based on the PM model. However, unlike PM, the processes of transpiration and evaporation are separated. This enables evapotranspiration from pasture with variable ground cover to be estimated through explicitly specifying energy exchange at the canopy and the soil (Allen et al., 1998; Farahani & Bausch, 1995). For the current research, the use of crop coefficients has been explored, and the PM, PT, SWW and DCC models have been used to estimate PETc, and the methods compared, thus addressing Objective 6 (Section 1.4). The selected models provide a range of approaches commonly applied, but have different data input requirements and represent a range of model complexity.

### 2.4.1 Crop coefficients (Kc)

AET for a well-watered crop (i.e. PETc), can be estimated by crop coefficients, for which PETa is multiplied by a given crop coefficient (Kc) (Equation 2.37). In this approach the climatic conditions are incorporated into the PETa estimation and the vegetation characteristics are represented by the crop coefficient (Allen et al., 1998).

\[
\text{AET (or PETc)} = K_c \text{PETa}
\]  

Alternatively, if both AET and PETa are known, the crop coefficient for particular vegetation and ground cover conditions can be determined. The Kc is designed to estimate AET from PETa under standard conditions only, which refers to a crop (i.e. pasture) grown under disease-free, well-fertilised, and
optimum soil water conditions that achieves maximum production under the given climatic conditions. Further adjustments can be made where non-standard conditions occur, such as water stress, which have been detailed by Allen et al. (1998) and Equation 2.2.

Crop coefficients are representative of the differences in crop height, albedo, canopy resistance, and soil evaporation of a specific crop, compared with the reference surface used in the calculation of PET (Equation 2.42). The $K_c$ of an annual crop therefore changes throughout the growing season in response to changes in plant development, ground cover, and plant age and maturity. Figure 2.8 illustrates the typical pattern of a crop coefficient curve for pasture. Growth cycles have been separated into four stages: the initial growth stage, the development stage, the mid-season stage, and the late season stage, each of which contribute to the crop coefficient curve. The initial growth stage applies up to a ground cover of 10%, while the mid stage is reached once canopy closure occurs (i.e. 95% ground cover (Brougham, 1958)).

When forage crops or pasture are harvested or grazed several times throughout the growing season, each defoliation event results in the end of a ‘sub’ growing season and its associated $K_c$ curve, and commences a new ‘sub’ growing season and $K_c$ curve. This leads to a series of ‘sub’ curves that make up a $K_c$ time-series for the entire growing season. For a pasture with a maximum height of 150-300 mm under a regular grazing rotation, Allen et al. (1998) identifies $K_c$ values of 0.4 in the initial growth stage that increase linearly during the crop development stage to 0.85-1.05 in the mid-season growth stage at full canopy cover. Under regular grazing, the end stage is unlikely to be reached. However, these are based on the results of studies predominantly in the Northern Hemisphere, and therefore the validity of their application in New Zealand is uncertain, and is part of the current investigation.

![Figure 2.8](image)

Figure 2.8  Schematic variation of the crop coefficient ($K_c$) over the growing season for rotationally grazed pasture. Adapted from Allen et al. (1998).

Limited research into appropriate $K_c$ values for pasture in New Zealand has been undertaken. The use of $K_c$ values within New Zealand has therefore often been based on previously published values,
including those by Allen et al. (1998) (Figure 2.8) or Doorenbos and Pruitt (1975) (Green et al., 1999; Hedley & Yule, 2009). Alternatively, for pasture a single \( K_c =1 \) has also been assumed, which results in estimates of \( \text{AET} = \text{PET}_0 \) (Brown et al., 2010). Bright (2009a) developed a \( K_c \) time series for irrigated perennial ryegrass and white clover pasture for Canterbury based on lysimeter measured AET, as shown in Figure 2.9. That study was based on data obtained from one site only and hence one soil type and climatic environment, and the values were likely elevated due to possible run-off effects (Clothier et al., 2009). This study aims to expand the research undertaken by Bright (2009a) through the inclusion of additional sites.

![Figure 2.9 Derived crop coefficient time series for irrigated perennial ryegrass/white clover pasture in Central Canterbury. Redrawn from Bright (2009a).](image)

### 2.4.2 Potential evapotranspiration models

#### 2.4.2.1 Penman-Monteith (PM) and the FAO modified Penman-Monteith (PM\textsubscript{FAO}) models

The PM method is a mechanistic equation that uses climate data to estimate PET and is the current best practice method (Allen et al., 1998; Irmak et al., 2006; Jensen, 1973; Jensen et al., 1990; Sentelhas et al., 2010). Its development occurred over time, initially proposed by Penman (1948) for describing evaporation from saturated surfaces (Equation 2.38). It was later modified by the Food and Agriculture Organization (FAO) and referred to as the modified Penman equation. This was then extended in 1981 by Monteith (1981), and enabled the estimation of \( \text{PET}_0 \) from a cropped surface by factoring in canopy resistances (Allen et al., 1998; Ehlers & Goss, 2003), assuming an actively-growing, uniform, closed canopy crop with adequate water supply. The result was the PM equation (Equation 2.39).

\[
ET = \frac{\Delta R_n - G + \rho_a C_p (e_s - e_a)}{\lambda (\Delta + \gamma)} 
\tag{2.38}
\]

\[
\lambda ET = \frac{\Delta R_n - G + \rho_a C_p (e_s - e_a)}{\Delta + \gamma (1 + \frac{\Delta}{\gamma})} 
\tag{2.39}
\]
where λ, the latent heat of vaporization, is equal to 2.45 MJ/kg, Rn is the net radiation, G the soil heat flux, ρa the mean air density, Cp the specific heat of the air at constant pressure, Δ the slope of the saturation vapour pressure temperature relationship, es and ea the saturation and actual vapour pressures in the air above the crop, respectively, rs the (bulk) surface resistance, ra the aerodynamic resistance and γ the psychrometric constant. Where rs or ra are not measured, they can be estimated using the method developed by Allen et al. (1998) as follows:

\[ r_s = \frac{r_1}{LAI_{\text{active}}} \]

\[ ra = \frac{208}{u_2} \]

where \( r_1 \) represents the bulk stomatal resistance of the well-illuminated leaf, LAI_{\text{active}} the active sunlit leaf area index (LAI), and \( u_2 \) the wind speed at a height of 2 metres above the ground surface. Estimates of evapotranspiration using the PM method can be most sensitive to these resistance parameters, which account for the control vegetation has on water use. Their accurate measurement and/or estimation are essential for accurate estimates of evapotranspiration (Allen & Daniel, 2005; Beven, 1979; Sumner & Jacobs, 2005).

An FAO panel review of methodologies on crop water requirements identified the PM equation as the most accurate practice for estimating PET (Allen et al., 1998). However, according to Atwell et al. (1999) the complexity of directly measuring \( r_s \) and \( r_a \) lead to the FAO modification of the PM equation. This defined a hypothetical reference crop for estimating PET_o as being of 0.12 m in height, with a fixed surface resistance of 70 s/m and albedo of 0.23 (Allen et al., 1998) (Section 2.2.1). The FAO version of the PM equation (PM_{FAO}) is as follows:

\[ PET_o = \frac{0.408 \Delta (R_n - G) + \gamma \frac{900}{\Pi 273} u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34 u_2)} \]

where, T refers to the air temperature. The PM_{FAO} method uses standard climate data for the estimation of PET_o, being solar radiation, air temperature, air humidity (or rather the saturation vapour pressure deficit), and wind speed. However, Allen et al. (1998) identified that where data for some of these input variables are unavailable, the use of the PM_{FAO} method is limited. To overcome this Allen et al. (1998) derived a number of equations enabling missing humidity, radiation, or wind speed data to be estimated while still yielding satisfactory results (Trajkovic & Kolakovic, 2009).

### 2.4.2.2 Priestley-Taylor (PT)

The Priestley-Taylor (PT) method (Priestley & Taylor, 1972) is another commonly adopted approach in the estimation of PET. It is a simplification of the original Penman (1948) combination equation. The data requirements of the PT method are much less compared with PM, requiring only net radiation and temperature data and an empirical constant ‘\( \alpha \)’ to replace the aerodynamic component in the Penman method (Jensen et al., 1990), as follows:

\[ \text{PET}_c = \alpha \frac{R_n - G}{}\]
An empirical constant ‘α’ value of 1.26 was proposed by Priestley and Taylor (1972) and has been successfully adopted by numerous others (Eichinger et al., 1996; Jensen et al., 1990; McAneney & Itier, 1996; McAneney & Judd, 1983). The value of 1.26 is considered an average value, representative of a closed canopy, extensive wet surface crop under humid conditions where advection is low. Semi-arid to arid climates are represented by values higher than 1.26. Within a New Zealand setting, however, a wide range of values has been published. For example, values of 1.17-1.3 have been reported for pasture and crops under non-advective conditions in the Manawatu (Clothier et al., 1982; Green et al., 1984; Kenny et al., 1995; Scotter et al., 1979). Woodward et al. (2001) also reported values of ~0.63 to >2 for New Zealand, but that 60% of the time values exceed 1.26 due to the aerodynamic influence. Jamieson (1982) and McAneney and Judd (1983) both maintained the value of 1.26 for Canterbury and the Waikato, respectively, given by Priestley and Taylor (1972). A value of 1.26 has therefore been used in the estimation of PT PETc in this study.

2.4.2.3 Dual crop coefficient model (DCC)

An alternative to the single Kc value or time series has been developed (Allen et al., 1998; Jensen et al., 1990; Wright, 1982), for which Kc is separated into a basal crop coefficient (Kcb) and an evaporation coefficient (Ke), and referred to as the dual crop coefficient model (DCC). Kcb represents transpiration from the crop when soil water is not limiting, while Ke is the evaporation component, representing evaporation from the soil surface. Kc using the DCC model is calculated using Equation 2.44.

\[ K_c = K_{cb} + K_e \]  

2.44

Kcb and Ke can be determined as follows:

\[ K_{cb} = K_{cb(Tab)} + [0.04(u_2 - 2) - 0.004(RH_{\min} - 45)] \left(\frac{h}{3}\right)^2 \]  

2.45

\[ K_e = K_r(K_{c\ max} - K_{cb}) < f_{ew}K_{c\ max} \]  

2.46

where, \( K_{cb(Tab)} \) is the value for \( K_{cb\ mid} \) or \( K_{cb\ end} \), as given by Allen et al. (1998) (Figure 2.8), RH\( \min \) is the minimum relative humidity, \( h \) is the average canopy height, \( K_r \) a dimensionless evaporation reduction coefficient, \( K_{c\ max} \) the maximum Kc value following rainfall or irrigation, and \( f_{ew} \) the exposed, wetted fraction of the soil. The DCC model allows for improved estimates of Kc compared with the PM and PT methods by accounting for the effect of variation in canopy cover on the potential for soil evaporation, and is therefore used for irrigation scheduling. Goodwin et al. (2012) and Dragoni et al. (2004), for example, researched appropriate Kcb values for orchards and Poblete-Echeverria and Ortega-Farias (2013) for grapevines to improve calculations of actual water use and improve irrigation efficiency. The method improved estimations of water use by 10% compared with the use of the published values in
Allen et al. (1998). Hatfield and Allen (1996), however, found the PM model to provide more accurate, consistent estimates of water use than the DCC approach.

### 2.4.2.4 Shuttleworth-Wallace model (SWW)

The Shuttleworth-Wallace model (Shuttleworth & Wallace, 1985), like PM, is a one dimensional combination model. However, as with the DCC model, it separately estimates soil surface evaporation and canopy transpiration, thereby enabling the transition in evapotranspiration to be described between bare substrate and a closed canopy. In doing so, the representation of the soil-canopy-atmosphere system is improved compared with that of a single layer model (Ershadi et al., 2015). The model is an extension of the PM equation, and incorporates many of the same relationships and meteorological data requirements. However, unlike the PM, it does not take a ‘big leaf’ approach. Accordingly, the SWW model is highly complex and demands a number of input data representing the land surface characteristics, including plant canopy and residue coverage, surface and aerodynamic resistances, and net radiation partitioned between plant canopy and the soil surface (Odhiambo & Irmak, 2011; Shuttleworth & Wallace, 1985; Thornley & France, 2007; Zhou et al., 2006), as illustrated by Equations 2.47 to 2.54.

\[
\lambda ET = C_c PM_c + C_s PM_s
\]

\[
PM_c = \frac{\Delta A + \rho C_p D - \Delta r_{ac} A_s}{\Delta + \gamma (1 + r_c^s/(r_a^s + r_c^s))}
\]

\[
PM_s = \frac{\Delta A + \rho C_p D - \Delta r_{as} (A - A_s)}{\Delta + \gamma (1 + r_s^c/(r_a^s + r_s^s))}
\]

\[
C_c = \left(1 + (R_c R_a)/(R_s (R_c + R_a))\right)^{-1}
\]

\[
C_s = \left(1 + (R_s R_a)/(R_c (R_s + R_a))\right)^{-1}
\]

\[
R_a = (\Delta + \gamma) r_a^a
\]

\[
R_s = (\Delta + \gamma) r_s^s + \gamma r_s^s
\]

\[
R_c = (\Delta + \gamma) r_c^c + \gamma r_c^c
\]

where PM\(_c\) and PM\(_s\) relate to the canopy transpiration and soil surface evaporation, respectively, c denotes the canopy and s the soils in that C\(_c\) and C\(_s\) are weighing coefficients for the canopy and soil, respectively. A and A\(_s\) are the total energy fluxes leaving the crop and substrate, respectively, as sensible and latent heat per unit of ground area (MJ/m\(^2\)). D is the vapour pressure deficit (mb), r\(_a^s\) and r\(_a^c\) are aerodynamic resistances between the canopy and the reference height and between the soil surface and canopy (s/m), respectively. r\(_c^s\) is the bulk boundary layer resistance per unit area of vegetation (s/m), r\(_c^s\) is the bulk stomatal resistance of the canopy (s/m) and r\(_s^s\) the surface resistance of the soil (s/m). R\(_c\), R\(_s\) and R\(_a\) each represent canopy, aerodynamic and soil substrate resistances, respectively.
2.4.3 Model review and use

The PM model, including the FAO modified version (PM\textsubscript{FAO}), has been tested and validated both internationally and within New Zealand. Jensen \textit{et al.} (1990), for example, evaluated and compared the accuracy of 19 methods, each of which fell into one of four classifications: combination theory, radiation-based, temperature-based, or evaporation pan. The PM method was one of the eight combination methods evaluated in the study. The evaluation was undertaken for 11 sites, together representing a wide range in the magnitude of PET\textsubscript{c} under varying environmental and climatic conditions. The results of each method were compared with lysimeter-measured AET. The PM method gave results closest to the lysimeter measured values, with the ‘goodness of fit’ attributed to its ability to adjust the surface roughness and leaf area at each lysimeter location. However, the ‘big leaf’ approach of the PM model combines the heterogeneity of the land surface into a single evaporative process, creating no distinction between soil surface evaporation and canopy transpiration (Ershadi \textit{et al.}, 2015). This is likely to be appropriate in the case of a uniform, dense canopy that absorbs the available energy. However, the model does not take account of the increased importance of soil surface evaporation that can dominate under sparse canopies, such as a grazed pasture. In such cases, partitioning of evapotranspiration is essential to accurately monitor system hydrology and to improve water management practices (Kool \textit{et al.}, 2014).

Within New Zealand, the PM model is commonly used in the estimation of water use (Green \textit{et al.}, 1984; Green \textit{et al.}, 1999; Woodward \textit{et al.}, 2001). Judd \textit{et al.} (1986) found close agreement between PM estimates and the actual water use of kiwifruit, while Scotter and Heng (2003) found that use of the PM\textsubscript{FAO} method in New Zealand, where input climate data were limited, produced the most accurate estimates of PET\textsubscript{c}. When compared with the PT model, Clothier \textit{et al.} (1982) found both methods to provide daily estimates within 15-20% of lysimeter measured AET, and therefore recommended the use of the PT method over PM due to its simplicity. This was reiterated by McAneney and Itier (1996) who identified that uncertainties regarding stomatal behaviour and turbulent transport (i.e. estimations of $r_s$ and $r_a$) can make the PM method impractical as an operational tool.

Close agreement of PT with water use determined using the Bowen ratio-energy balance methods were reported by Clothier \textit{et al.} (1982) and Jamieson (1982), either when calculated over periods of weeks, under rain free conditions, or at half hourly intervals. Similarly McAneney and Judd (1983) and Scotter \textit{et al.} (1979) found PT to estimate PET sufficiently accurately for use in soil water balance studies.

Application of the SWW and DCC models in New Zealand to estimate PET\textsubscript{c} has been limited. For the SWW model, while its application internationally is well published, no literature could be found relating to its use in New Zealand. Furthermore, for both models, their application throughout the literature was predominantly for field crops rather than pasture.
Stannard (1993), for example, used the SWW model, along with the PM and PT models, to estimate PET$_c$ from wild land vegetation, and found the SWW model performed more accurately than the PM model, and provided similar predictions to the PT model. Odhiambo and Irmak (2011) compared measurements of AET for an irrigated soybean (*Glycine max* L. Merr.) crop using the Bowen Ratio Energy Budget with SWW estimates, and found the model was able to successfully follow the measured trends in AET. However, during early and later season growth stages where evaporation was dominant, there was poor agreement. Despite this, when measured and estimated ET were accumulated, many of the differences were less obvious due to the balancing effect of over- and under-estimations. Gardiol *et al.* (2003) compared estimates of evapotranspiration using the SWW and PM models for a maize crop, and found the SWW to perform more accurately than the PM when the vegetation density was low (i.e. LAI<4). This was due to the PM model neglecting soil surface evaporation during the early stages of growth. However, where the LAI>4, the PM was found to provide closer estimates of evapotranspiration to those measured. Ershadi *et al.* (2015) also compared PET$_c$ estimates for a range of biomes, the results from which identified the PM model to perform the best in grassland and shrubland sites, whereas the SWW rated highest for sparser canopies, including forests. Finally, Zhou (2011) recommended the use of the SWW over the PM due to its more robust physical basis and because it successfully accounts for the effect of changing land surface conditions on PET$_c$. Zhou (2011) therefore suggested that SWW estimates can be directly input into hydrological models. This has been done in the current thesis with the soil water flow model HYDRUS (Section 2.3.3.4).

Kato and Kamichika (2006) used the SWW model to estimate canopy transpiration and soil evaporation for a sparse sorghum field, which were then used to determine the basal crop and soil evaporation crop coefficients used in the DCC model from daily estimates of PET$_o$ using the PM$_{FAO}$ model. The $K_{cb}$ increased with increasing LAI rapidly and slowly below and above an LAI of 1.0, respectively, and the $K_e$ showed a positive relationship to increasing soil water content (SWC) at a depth of 150 mm. When compared with AET estimated using the Bowen Ratio Energy Budget, the DCC method was found to be an appropriate approach for estimating evapotranspiration.

Hedley and Yule (2009) used the DCC model to predict the effects of intermittent irrigation wetting events on basal crop transpiration and soil evaporation separately for an irrigated maize crop in the Manawatu District, New Zealand. Green (2008) used the DCC model to obtain estimates of potential transpiration from grapevines near Hastings, New Zealand. Liu and Luo (2010) evaluated whether or not the DCC method was suitable for calculating the actual daily evapotranspiration of winter wheat (*Triticum aestivum*) and summer maize crops in the North China Plain, with results compared against lysimeter-based measurements. Results of the review identified that the DCC model was effective at simulating total seasonal evapotranspiration, with a high Nash-Sutcliffe coefficient of 0.90 and low root
mean square deviation of 0.90 mm/d (or 10%) for winter wheat. However, under- and over-
estimations in the initial and later stages of crop development limited its use for short-term
simulations.

2.5 Statistical evaluation of modelled data

A range of methods for statistically evaluating modelled data exist. However, from a review of the
literature it does not appear that there is a standard process that is followed; rather it is left up to the
author to decide the approach to take. This conclusion is supported in a review by the American Society
of Civil engineers (ASCE, 1993), who highlight that although there has been a multitude of computer-
based simulation models developed in the past several decades, there do not appear to be commonly
accepted standards for evaluating the reliability of these models. From their review, ASCE
recommended that when evaluating modelled data, both visual and statistical comparisons be made
whenever data are presented. Visual presentation (i.e. graphic plots) provides a general overview of
model performance and provides an overall feeling for model capabilities. Quantitative assessment of
modelled results can be achieved by using one or more statistical goodness-of-fit criteria. Similarly,
Chai and Draxler (2014) suggest that any single statistical measure provides only one projection of the
model errors and, therefore, only emphasises a certain aspect of the error characteristics. Therefore,
a combination of metrics should be used.

Common statistical criteria applied throughout the literature include the coefficient of determination
\( r^2 \), the root mean square deviation (RMSD), which can be normalised to either the mean of the
observed data or to the range of the observed data (NRMSD), the Nash-Sutcliffe efficiency coefficient
(NSE), the mean bias error (MBE), the mean absolute error (MAE) as well as a general comparison of
the ratio of the observed to the simulated data, be it in relation to soil moisture, drainage volumes or
herbage mass accumulation.

Of these, the RMSD is commonly used throughout the literature to measure model performance
relating to evapotranspiration (Allen et al., 2006; Brown et al., 2012; Odhiambo & Irmak, 2011),
climatic research (Fletcher & Moot, 2007), hydrology (Dann et al., 2010), and pasture production and
photosynthesis (Li et al., 2011; Peri et al., 2002a; Peri et al., 2002b). The NSE coefficient, on the other
hand, is widely used in water resources to assess the predictive abilities of hydrologic models (Gandolfi
et al., 2006; Jain & Sudheer, 2008; Liu & Luo, 2010; McCuen et al., 2006; Sansoulet et al., 2008; Wöhling
& Vrugt, 2007; Zhou et al., 2012; Zhou et al., 2006), and has also been extended to comparing PETc
model performance (Ershadi et al., 2015). These two statistical criteria have therefore been used
throughout this thesis to compare the accuracy of simulated pasture growth, soil water flow and
evapotranspiration data with field measurements. Where appropriate, results have also been
supported with the use of statistical parameters including the $r^2$, the coefficient of variation (CV), the calculation of the mean bias and general comparisons of simulated and observed data on a percentage basis.

The NSE can be determined as follows:

$$\text{NSE} = 1 - \frac{\sum_{t=1}^{n}(O_t - S_t)^2}{\sum_{t=1}^{n}(O_t - \bar{O})^2}$$  

where $O_t$ and $S_t$ are the observed and simulated values at time $t$, respectively, $\bar{O}$ is the average observed value and $n$ is the number of samples. NSE coefficients can vary from 0-1. An NSE = 1 is indicative of a perfect fit between the observed and predicted values, while NSE = 0 indicates the model predictions are no more accurate than using the average of the observed data. Where the NSE is less than zero, the average of the observed data is a more accurate predictor than the model. However, if the measured values approach the mean value (i.e. the coefficient of variation is low), the denominator in the equation (Equation 2.55) approaches zero, and a negative NSE coefficient value can result with only minor model imprecision (ASCE, 1993).

The RMSD, and the RMSD normalised to the mean of the observed data (NRMSD) are calculated as follows:

$$\text{RMSD} = \left[\frac{\sum_{t=1}^{n}(O_t - S_t)^2}{n}\right]^{0.5}$$  

$$\text{NRMSD} = \frac{\text{RMSD}}{\bar{O}}$$  

The RMSD gives a measure or index of the absolute deviation between the simulated and observed data, whereas the NRMSD provides a relative deviation of the simulated from the observed and can therefore be used to compare datasets or models with different scales. With the NRMSD, a value of 0 represents a perfect fit between the observed and the predicted values, although a value less than 0.2 is generally indicative of an accurate representation by the model of the observed data (Mills, 2007). A common concern with the RMSD, however, is its sensitivity to outliers in that it gives errors with larger absolute values more weight than errors with smaller absolute values (Chai & Draxler, 2014). However, Chai and Draxler (2014) contend that the RMSD proves to be an effective method of determining model performance and suggest that penalising large errors, as is done by the MAE, will improve model performance, and make calculation of the sensitivity of certain model parameters difficult.

To gain further insight into causes of model deviations, the MSD, being the RMSD squared, values can be partitioned into three components (Dolling et al., 2005; Gauch et al., 2003; Moot et al., 2014): squared bias (SB), non-unit slope (NU) and lack of correlation (LC), as follows:

$$\text{MSD} = \text{SB} + \text{NU} + \text{LC}$$
\[ SB = (\bar{O} - \bar{S})^2 \]

\[ NU = (1 - b)^2 \times \left( \frac{\sum (S - \bar{S})^2}{n} \right) \]

\[ LC = (1 - r^2) \times \left( \frac{\sum (O - \bar{O})^2}{n} \right) \]

where \( \bar{O} \) and \( \bar{S} \) are the mean of the observed and simulated values, respectively, \( b \) is the slope of the least squared regression between the observed (y-axis) and simulated (x-axis) values and \( r^2 \) is the coefficient of determination.

Perfect equality is achieved when the observed is equal to the simulated, giving an MSD = 0. According to Gauch et al. (2003), deviation from this arises due to translation, rotation and/or scatter. Translation is where \( \bar{O} \neq \bar{S} \), leading to \( SB > 0 \). However, \( SB > 0 \) will also occur when \( b = 1 \), but the intercept \( a \neq 0 \). Rotation occurs when \( b \neq 1 \), and therefore \( NU > 0 \). Lastly, scatter results in an \( LC > 0 \) when \( r^2 \neq 1 \) due to errors. The three components are therefore additive and have clear and distinct meanings with transparent relationships with regression parameters \( b \) (NU), \( r^2 \) (LC) and \( a \) (SB, where \( b = 1 \) and \( a > 0 \)).

Gauch et al. (2003) highlight the superiority of using the MSD statistic for model selection over regression and correlation. Specifically, they identify that linear regression is often applied to variables that share no common interest, such as yield and fertiliser, and therefore there is no expectation that the intercept will be zero or the slope will be unity. Accordingly, the regression accounts for bias and NU, and therefore only LC will reduce the regression’s fit.

When interpreting results, different ‘winners’ can be selected if one model has the lowest MSD but a different model has the lowest LC component, which translates to the highest \( r^2 \) (Gauch et al., 2003). However, often a model’s problems with NU and SB are relatively easy to fix, unlike problems with LC. Accordingly, the MSD will rank models according to their merits, but the LC improves the ranking of the potential model merits after the relatively easily fixed defects have been corrected. Dolling et al. (2005), for example, reported improved predictions of biomass in response to reduced SB and NU components, and a subsequent increase in the LC. Similarly, Moot et al. (2014) reported improved shoot biomass predictions when model calibration led to an increase in LC from 53-93% and reductions in both SB and NU, resulting in a well distributed bias.

To enable clear understanding of the differences between model predictions, the process of separating the MSD into the SB, NU and LC has been applied to the simulated pasture growth, soil water flow and evapotranspiration results presented in this thesis.
2.6 Conclusions

This chapter reviewed relevant literature associated with the process of evapotranspiration, its measurement, and the influence of climate, pasture management and physiology and soil on evapotranspiration. Objective 1 was achieved through a critical review of existing methods of estimating evapotranspiration, and their application in New Zealand and internationally was summarised.

Evapotranspiration is a key, yet relatively complex, process in the development and growth of plants and has formed the focus of many studies. Much of the literature reviewed agreed that the Penman-Monteith method is the best-practice method for estimation of evapotranspiration, and recommends its use where possible above other existing methods. However, some advocated the use of the Priestley-Taylor method due to its simplicity and ability to provide estimates with a similar degree of accuracy to PM. The development of crop coefficients, which enable the estimation of AET from PET data, and definition of relationships between ET and crop canopy characteristics, have also been well reported throughout the literature. In some studies, however, the ability to separate estimates of evaporation and transpiration were investigated and the results highlighted the benefits of using models such at the DCC and SWW models. However, these demand detailed inputs relating to the land surface and canopy.

In relation to pasture within New Zealand, it has been identified that there is a significant gap in the research to date. Specifically, there is limited understanding of evapotranspiration from irrigated, grazed dairy pastures, and therefore its estimation. While a number of methods are used to estimate evapotranspiration, they haven’t been well tested for an irrigated grazed dairy pasture, where the canopy is regularly subjected to defoliation. Accordingly, this has the potential to result in under- or over-estimations of water use, and has implications for the management of water at both the farm and region level. This thesis will go some way towards closing the current knowledge gap through addressing the hypothesis and associated objectives set out in Chapter 1.
Chapter 3
Quantifying Growth of Well-Watered Lysimeter-Grown Perennial Ryegrass-Based Pastures under Commercial Canterbury Dairy Farming Operations

3.1 Introduction

The hypothesis of this research is that there is sufficient spatial variation in pasture water use to preclude the use of a single crop coefficient time series at all locations for accurately modelling evapotranspiration from pasture. To test this hypothesis, evapotranspiration needs to be determined, for which inputs of daily canopy variables of leaf area and height are required (Section 2.4). Furthermore, the appropriate interpretation and understanding of evapotranspiration data necessitates an understanding of the development of the canopy. Accordingly, the second objective (Section 1.4) of this research was to describe and quantify growth of a well-watered, lysimeter-grown, perennial ryegrass/white clover sward within a commercial Canterbury dairy farming operation. The third objective involved the evaluation and calibration of the pasture growth model ‘DairyMod’ against the observed pasture growth data, after which the model was used at other sites across Canterbury to estimate pasture growth where it was not measured.

To achieve Objective 2, lysimeter-grown herbage mass, leaf area and height, botanical composition and pasture fertility are quantified for Larundel Dairy Farm, West Eyreton, Canterbury, from 09/09/2011 to 07/09/2012 (dd/mm/yyyy). In doing so, a determination of whether the lysimeter-grown pasture was representative of that grown in the wider paddock was possible, as was a direct comparison of the pasture performance with other published data for Canterbury.

To achieve Objective 3, DairyMod was calibrated against the observed pasture growth at Larundel Dairy Farm, and then used to quantify pasture growth (herbage accumulation, leaf area, height and nitrogen fertility) at Three Springs Dairies and Pendo Farms. The measured and simulated pasture data were used in the estimation of PETc at each of the sites in Chapter 4. At Larundel Dairy Farm, the data were also used to compare daily PETc estimations using measured and modelled canopy data.
3.2 Methods and Materials

3.2.1 Site

The experimental sites, Larundel Dairy Farm (LDF), Three Springs Dairies (TSD) and Pendo Farms (PF) were operating as commercial dairy farms throughout the experiment. The three sites are spread across the mid to north Canterbury Plains, stretching from just south of the Rakaia River to just north of the Waimakariri River. They represent varying climatic environments and soil types common to the Canterbury region. The topography of all sites is flat. The locations of the three sites are shown in Figure 3.1 and summarised in Table 3.1.

Table 3.1 Location and elevation above mean sea level of field experiment sites Larundel Dairy Farm, Three Springs Dairies, and Pendo Farms.

<table>
<thead>
<tr>
<th>Site</th>
<th>Nomenclature</th>
<th>Area</th>
<th>Location (NZGD 2000)</th>
<th>Elevation (m a.s.l.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larundel Dairy Farm</td>
<td>LDF</td>
<td>West Eyreton</td>
<td>43° 21.3'S, 172° 25.8'E</td>
<td>88</td>
</tr>
<tr>
<td>Three Springs Dairies</td>
<td>TSD</td>
<td>Methven</td>
<td>43° 40.4'S, 171° 35.5'E</td>
<td>305</td>
</tr>
<tr>
<td>Pendo Farms</td>
<td>PF</td>
<td>Dorie</td>
<td>43° 49.8'S, 172° 5.6'E</td>
<td>55</td>
</tr>
</tbody>
</table>

Figure 3.1 Map showing the locations of field experiment sites Larundel Dairy Farm, Three Springs Dairies, and Pendo Farms across the Canterbury Plains.
3.2.2 Soil

One of the main factors contributing to the selection of the sites for this study was soil type. Each site was chosen where the soil represented one of the dominant soil series in the area. Soil surveys prior to the installation of lysimeters and profile descriptions at the time of lysimeter installations were undertaken by an experienced local pedologist (Trevor Webb, Landcare Crown Research Institute (Landcare)) for each site.

3.2.2.1 Larundel Dairy Farm (LDF) soil description

At LDF, the soils consisted of a shallow Darnley silt loam (Inceptic Hapludalf, USDA Soil Taxonomy, (U.S.D.A., 1984)) (Dr Sam Carrick, pers. comm., 22 Jan. 2015). Darnley shallow silt loam soils are characterised on Landcare’s database (S-Map) (Landcare Research, 2013) as being shallow, moderately well-draining, with a medium plant available water content of up to 110 mm for the 700 mm soil profile. The top soil is slightly stony (0-7%) while the extremely gravelly nature of the soil at deeper depths (up to 60%) creates a potential rooting barrier. Permeability is moderate over low, although there is a high risk of bypass flow occurring. Aeration in the root zone is moderately restricted. Photos of the lysimeter soil profiles are given in Plate 3.1. Profile descriptions of the three lysimeters at the LDF site are given in Appendix 1, based on the soil survey undertaken by Trevor Webb.

Plate 3.1 Soil profiles within the pit from which lysimeters L1-L3 at Larundel Dairy Farm were extracted (source: T. Webb, Landcare Research Ltd). Tape measure extended to 1500 mm.

The soil moisture content of the soil (0-700 mm) at field capacity (FC) (23%) and wilting point (WP) (11.8%) was determined from site measured gravimetric soil water retention curve data (Table 3.2), whereby field capacity was taken to be at a soil water potential of -10 kPa and wilting point at -1,500 kPa (McLaren & Cameron, 1996). The soil moisture was assumed to become limiting to the canopy at 17.4%, which was half way between field capacity and wilting point (Section 2.3.2.2).
Soil water retention measurements provided in Table 3.2 for the soil layers 0-180 mm and 180-520 mm were determined from soil cores taken from the experiment site by Dr Sam Carrick of Landcare in December 2011. No measurements were taken below 520 mm, but Rosetta Lite, version 1.1 (Rosetta) (Schaap et al., 2001) (Section 2.3.3.4) was used to fit van-Genuchten (1980) parameters to the soil textural data (Appendix 1). The estimated van-Genuchten (1980) parameters were then used to predict the soil water content at specific matric potentials for the 520-700 mm soil layer using Equation 2.32.

The measured/estimated soil water content related only to the finer material, and therefore did not account for the presence of stones within the profile, which comprised ~7% of the soil volume between 0-180 mm, ~30% from 180-520 mm and ~50% below 520 mm (Appendix 1). The actual water content of the soil at each matric potential (Table 3.2), adjusted for the volume of stones (%) present was determined using the method given by Riddell (1979) as follows:

\[ SMC^* = SMC \times (1 - \text{stone(v/v \%)/100}) \]  

Table 3.2  
Dry bulk density and gravimetric soil water content (%) at varying matric potentials for a Darnley silt loam soil, West Eyreton, Canterbury. Values in brackets represent the soil water contents adjusted for the soil stone content.

<table>
<thead>
<tr>
<th>Soil depth (mm)</th>
<th>0</th>
<th>-10</th>
<th>Matric potential (kPa)</th>
<th>Dry bulk density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-180³</td>
<td>47.7</td>
<td>41.7</td>
<td>39.9</td>
<td>44.5</td>
</tr>
<tr>
<td></td>
<td>(44.3)</td>
<td>(38.8)</td>
<td>(37.1)</td>
<td>(31.1)</td>
</tr>
<tr>
<td>180-520³</td>
<td>44.5</td>
<td>33.3</td>
<td>32.0</td>
<td>36.6</td>
</tr>
<tr>
<td></td>
<td>(31.1)</td>
<td>(23.3)</td>
<td>(22.4)</td>
<td>(18.3)</td>
</tr>
<tr>
<td>520-700³, ¹</td>
<td>36.6</td>
<td>15.4</td>
<td>10.3</td>
<td>3.6</td>
</tr>
<tr>
<td></td>
<td>(18.3)</td>
<td>(7.7)</td>
<td>(5.2)</td>
<td>(3.8)</td>
</tr>
</tbody>
</table>

Note 1: Data for the 0-180 and 180-520 mm soil layers are the means of two replicates, taken by S. Carrick of Landcare Research, December 2011.
Note 2: Values estimated from particle size distribution data (Appendix 1) using Rosetta (Schaap et al., 2001) and Equation 2.32.
Note 3: Values in brackets are the soil water contents adjusted for the soil stone contents, on the basis that stones accounted for ~7% of the volume for 0-180 mm, ~30% for 180-520 mm and ~50% for 520-700 mm, as per Appendix 1.

The results of a soil test carried out in July 2013 identified the soil fertility to be moderate at the site (Table 3.3).
Table 3.3 Results of soil testing within lysimeter paddocks at Larundel Dairy Farm (LDF), Three Springs Dairies (TSD) and Pendo Farms (PF).

<table>
<thead>
<tr>
<th>Site</th>
<th>Date</th>
<th>Depth (mm)</th>
<th>pH (H₂O)</th>
<th>Olsen P (mg/kg)</th>
<th>SO₄²⁻ (mg/L)</th>
<th>Ca²⁺ (me/100g)</th>
<th>Mg²⁺ (me/100g)</th>
<th>K⁺ (me/100g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LDF</td>
<td>July 2013</td>
<td>0-75</td>
<td>6.0</td>
<td>39</td>
<td>7</td>
<td>10.5</td>
<td>1.82</td>
<td>0.54</td>
</tr>
<tr>
<td>TSD</td>
<td>March 2011</td>
<td>0-75</td>
<td>6.5</td>
<td>16</td>
<td>5</td>
<td>13.6</td>
<td>1.02</td>
<td>0.54</td>
</tr>
<tr>
<td>PF</td>
<td>December 2012</td>
<td>0-150</td>
<td>6.6</td>
<td>26</td>
<td>-</td>
<td>8.0</td>
<td>1.68</td>
<td>0.55</td>
</tr>
</tbody>
</table>

Normal range levels

5.7-6.2  20-30  10-20  4-12  0.6-1.6  0.3-0.6

Note: Soil samples were analysed using Ministry of Agriculture and Fisheries Quick Test MAF procedures. The normal range levels were taken from the Hill Laboratories Crop Guides for ryegrass and mixed pasture (Hill Laboratories, 2015).

3.2.2.2 Three Springs Dairies soil description

At TSD, the soils consisted of Lismore stony silt loams (Udic Haplustep loamy skeletal, USDA Soil Taxonomy, (U.S.D.A., 1984)) (Di et al., 2007). A visit by T. Webb (pers. comm., 12 Oct. 2012) to the site prior to the lysimeter installation identified that border-strip irrigation effects were present. Some areas had only a thin (100-120 mm) topsoil because of scraping, while areas identified as fill sites had much deeper (300-400 mm) topsoils. The lysimeter site chosen was one that was considered relatively uninfluenced by previous border strip development, having topsoils of ~200 mm. All three lysimeter profiles had the same sequence of horizons, although slightly different thicknesses (Appendix 2). The stone content of the upper 300 mm was ~20%, which increased to 50-60% at lower depths. Photos of the lysimeter soil profiles are given in Plate 3.2.

No impediments to drainage or root growth were present, although the subsoil had a weakly developed clay pan, so it was considered to be bordering on a Darnley soil. According to S-Map (Landcare Research, 2013), Lismore stony silt loams are characterised as shallow, well-draining soils with no aeration problems or significant impediments to root growth. Permeability is moderate over rapid. The plant available soil water content of Lismore soils typically range between ~100-120 mm for a 700 mm soil profile.
Plate 3.2 Soil profiles of lysimeter cores L1-L3 at Three Springs Dairies. Actual lysimeter core numbers of each photo are unknown (source: M Flintoft, Aqualinc Research Limited). (a) and (c) show the upper ~470 mm of the soil profile, (b) shows the full 700 mm profile.

The soil moisture content of the soil (0-700 mm) at FC and WP was determined from soil water retention data (Section 4.2.4.2) to be 27 and 14%, respectively. The soil moisture was assumed to become limiting to the canopy at 20%, half way between FC and WP (Section 2.3.2.2).

The results of a soil test carried out in March 2011 identified the soil fertility to be moderate to low (Table 3.3).

3.2.2.3 *Pendo Farms soil description*

At the PF site the lysimeter cores were cut from Templeton moderately deep silt loam soils (Udic Haplustepts, USDA Soil Taxonomy, (U.S.D.A., 1984)) (Di *et al.*, 2007). Profile descriptions of the three lysimeters are given in Appendix 3. The soil had an even texture and moderate permeability throughout, with a PAW of ~120-140 mm. The profiles of Lysimeters L1 and L3 were identical, while the L2 profile had an AB horizon from 230-290 mm. Gravels were evident from ~700-750 mm, below the base of the lysimeter cores. Photos of the lysimeter soil profiles are given in Plate 3.3.

The S-Map database (Landcare Research, 2013) identifies moderately deep Templeton soils as stoneless, moderately well-draining soils with moderately limited aeration and no significant obstacles to root growth. Permeability of these soils is moderate over slow.
Plate 3.3  Soil profiles of lysimeter cores L1 (a), L2 (b), and L3 (c) at Pendo Farms (source: T. Webb, Landcare Research Ltd). The dashed red line illustrates the approximate depth (700 mm) of the lysimeter cores.

The soil moisture content of the soil (0-700 mm) at FC and WP was determined from soil water retention data (Section 4.2.4.2) to be 34.1 and 16.3%, respectively. The soil moisture was assumed to become limiting to the canopy at 25.2%, half way between FC and WP (Section 2.3.2.2).

The results of a soil test carried out in December 2012 identified the soil fertility to be moderate (Table 3.3).

3.2.3 Climate

Climate stations were installed on-site by NIWA and the Canterbury Regional Council at LDF, TSD, and PF as part of the Waterscape Programme (Section 1.1) (Table 3.4).

Global radiation (MJ/m²), mean air temperature (°C), mean relative humidity (%), mean wind speed (m/s), atmospheric pressure (hPa), and rainfall (mm) were measured automatically at 10-minute intervals, excluding PF where measurements were hourly. Measurements from each of the climate stations were automatically logged and telemetered over a wireless mobile network for retrieval and analysis through NIWA’s national climate database, CliFlo (NIWA, 2013).
Table 3.4  Climate station agent numbers, locations, and periods of record for climate stations used to obtain global radiation, air temperature, humidity, wind speed and atmospheric pressure data for Larundel Dairy Farm, Three Springs Dairies and Pendo Farms.

<table>
<thead>
<tr>
<th>Field site</th>
<th>Climate station</th>
<th>Agent number</th>
<th>Location (NZGD 2000)</th>
<th>Record period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larundel Dairy Farm</td>
<td></td>
<td>39224(^1)</td>
<td>43° 21.4'S, 172° 25.9'E</td>
<td>12 November 2007- on-going</td>
</tr>
<tr>
<td>Three Springs Dairies</td>
<td></td>
<td>37920</td>
<td>43° 40.6'S, 171° 35.3'E</td>
<td>29 Jan 2010 - on-going</td>
</tr>
<tr>
<td>Pendo Farms</td>
<td></td>
<td>38866</td>
<td>43° 49.9'S, 172° 5.6'E</td>
<td>31 August 2010 - on-going</td>
</tr>
</tbody>
</table>

Note 1: Climate station agent number was previously 35463 for Larundel Dairy Farm site, but was replaced in October 2011 by 39224.

Errors were identified in the measured global radiation data at LDF and PF throughout the experiment, caused by failures in the data logging system at LDF and a faulty pyranometer at PF. The methods used to investigate and correct the data at the lysimeter sites are detailed in Appendix 4. Global radiation data presented in this thesis are the corrected data.

3.2.3.1  Rainfall, irrigation and evapotranspiration

Over the experimental period (09/09/2011-07/09/2012), rainfall at each site was similar to the long-term mean (LTM) values (Table 3.5). TSD was the wettest with 988 mm of rain (LTM of 928 mm), followed by LDF with 746 mm (LTM 764 mm) and then PF with 660 mm (LTM 676 mm). Of the 660-988 mm, 60-69% (442-678 mm) fell during the eight-month irrigation season (September-April), again similar to the LTM. Daily rainfall (Figure 3.2) exceeded 40 mm on two occasions (19/10/2011 and 16/10/2011) at LDF and TSD and on one occasion at PF (19/10/2011), reaching maximums of 48.6, 55.6 and 55.8 mm/d at the three sites, respectively.

In addition to in-season rainfall, 225 mm of irrigation were applied at LDF, 173 mm at TSD and 144 mm at PF, bringing the total irrigation season water inputs to 672, 851 and 586 mm, respectively (Table 3.5). At LDF, there were 34 irrigation events with 6.6 mm applied on average every five days, with a maximum of 12.6 mm applied on any one day (Figure 3.2). At TSD, there were 31 irrigation events with 5.6 mm applied on average every 2-3 days, at a maximal rate of 14.8 mm/d (Figure 3.2). There was a period of 76 days between the first and last irrigation (28/11/2011-2/4/2012) at TSD, while at LDF there were 180 days (5/10/2011-2/4/2012). At PF, irrigation was spread out over 156 days (2/11/2011-06/4/2012) with an average of 3.5 mm applied every four days, resulting in 41 irrigations. A maximum of 9.4 mm of irrigation was applied on any one day (Figure 3.2). Daily maximum rainfall and irrigation intensities, calculated from the 10-minute data, ranged from a minimum of 1.2 mm/h at each of the three sites up to maximums of 27.6, 64.8 and 22.8 mm/h at LDF, TSD and PF, respectively, and were generally highest during the peak of the irrigation season (November-January) (Figure 3.3).
Annual \( \text{PET}_o \) at each site (Table 3.5), which represents atmospheric demand (Section 2.2.1), was within 9-18% of the LTM values, totalling 896 mm at LDF, 878 mm at TSD, and 921 mm at PF. Accordingly, PF had the lowest rainfall but highest \( \text{PET}_o \) demand. During the irrigation season, \( \text{PET}_o \) at the three sites was 85-87% of the annual total. \( \text{PET}_o \) varied throughout the year (Figure 3.2) and was highest from November-January, peaking at 7 mm/d at each of the three sites, and lowest from June-August with minimums of <0.5 mm/d at all three sites.

Figure 3.2 provides a soil water budget over the experimental period, showing the daily \( \text{PET}_o \), rainfall, irrigation and potential soil moisture deficits, with and without irrigation applied. The potential soil moisture deficits were calculated using the daily \( \text{PET}_o \) and rainfall and irrigation data, assuming a starting soil moisture deficit of zero on 07/09/2011, as follows:

\[
\text{PSMD} = \text{PSMD}_{i-1} - R(-I) + D + RO + \text{PET}_o \\
\]

where PSMD is the potential soil moisture deficit (mm) for the 700 mm lysimeter soil profiles, \( \text{PSMD}_{i-1} \) is the PSMD on the previous day, \( \text{PET}_o \) is the reference crop potential evapotranspiration calculated using Equation 2.42, \( R \) and \( I \) represent inputs of rainfall and irrigation, and \( D \) and \( RO \) outputs of drainage and run-off. Drainage and run-off were assumed to, combined, equal water inputs in excess of field capacity.

For the 700 mm lysimeter soil profiles, the PSMD without irrigation reached a maximum of 300 mm at LDF, 135 mm at TSD and 384 mm at PF. While irrigation enabled a lower soil moisture deficit to be maintained, the maximum PSMD with irrigation at LDF was still high, being 106 mm at LDF, 55 mm at TSD and 240 mm at PF. These data suggest that without irrigation, soil moisture may have been a limiting factor to pasture growth at all three sites, but with irrigation, the potential for water stress was largely removed at TSD (Section 3.2.2). At LDF and PF, even with irrigation, the potential water deficit was greater than the critical deficit.
Figure 3.2  Daily potential reference crop evapotranspiration (PET<sub>o</sub>) (—), stacked daily precipitation including rainfall (■) and irrigation (▲) and the potential soil moisture deficits with (—) and without (---) irrigation from 07/09/2011 to 14/09/2012 at Larundel Dairy Farm (LDF), Three Springs Dairies (TSD) and Pendo Farms (PF). PET<sub>o</sub> was calculated using Equation 2.42 with daily climate data sourced from the NIWA on-site meteorological stations 39224 (LDF), 37920 (TSD) and 38866 (PF).
Table 3.5 Rainfall, irrigation and reference crop potential evapotranspiration (PET<sub>T</sub>) for Larundel Dairy farm (LDF), Three Springs Dairies (TSD) and Pendo Farms (PF). Values presented are the annual (07/09/2011 to 14/09/2012) and irrigation season (months September to April) values for the long-term mean (LTM) and for the experimental period. Irrigation season values are in brackets.

<table>
<thead>
<tr>
<th>Field site</th>
<th>Rainfall (mm)&lt;sup&gt;1,3&lt;/sup&gt;</th>
<th>Irrigation (mm)</th>
<th>PET&lt;sub&gt;T&lt;/sub&gt; (mm)&lt;sup&gt;2,3&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>07Sep11-14Sep12</td>
<td>LTM</td>
<td>07Sep11-14Sep12</td>
</tr>
<tr>
<td>LDF</td>
<td>746 (447)</td>
<td>764 (474)</td>
<td>(225)</td>
</tr>
<tr>
<td>TSD</td>
<td>988 (678)</td>
<td>928 (633)</td>
<td>(173)</td>
</tr>
<tr>
<td>PF</td>
<td>660 (442)</td>
<td>676 (414)</td>
<td>(144)</td>
</tr>
</tbody>
</table>

Note 1: LTM rainfall data were sourced from NIWA’s virtual climate network (VCN) stations 20153 (LDF), 16989 (TSD), and 19019 (PF), for the period 1972-2013.
Note 2: LTM PET<sub>T</sub> was calculated using Equation 2.42 with solar radiation, air temperature, relative humidity and wind speed data from NIWA’s VCN stations 20153 (LDF), 16989 (TSD), and 19019 (PF), for the period 1997-2013.
Note 3: Experimental period data were sourced from NIWA’s on-site meteorological stations 39224 (LDF), 37920 (TSD), and 38866 (PF) (Sections 3.2.3.2 & 3.2.3.3). PET<sub>T</sub> was calculated using Equation 2.42. Solar radiation data for LDF and PF were the corrected values (Appendix 4).

Figure 3.3 Daily maximum rainfall and irrigation intensities (mm/h) recorded at Larundel Dairy Farm (■), Three Springs Dairies (■) and Pendo Farms (■) from 07/09/2011 to 14/09/2012, calculated from 10-minute rainfall and irrigation measurements.

3.2.3.2 Air temperature and solar radiation
Air temperature and solar radiation followed an expected seasonal pattern of highest values in summer and lowest in winter. January 2012 was the warmest month for all sites with mean daily air temperatures of 14.3-15.7°C, while June 2012 was coolest with means of 4.5-5.8°C (Figure 3.4). Across the three sites, minimum temperatures ranged between -9°C and 18°C and maximum between 6°C and 30°C. Mean daily temperatures over the experiment were between -3°C and 20°C, and averaged 10°C at LDF and TSD and 11°C at PF. Monthly averaged mean daily solar radiation peaked at 21-24 MJ/m²/d in November 2011 and January 2012 at the three sites and reduced to minimum values of 4.6-5.4 MJ/m²/d in June 2012 (Figure 3.5).
3.2.3.3 Relative humidity and wind speed

Monthly averaged mean daily relative humidity varied throughout the year at all sites (Figure 3.6). Values were lowest at 67-70% in November 2011 and reached a maximum in August 2012 of 83-86%. October was the windiest month at LDF with monthly averaged mean daily wind speeds of 3.5 m/s, while September 2012 was the windiest month for TSD and PF with mean daily wind speeds of 3.0 and 3.4 m/s, respectively. Wind speeds reduced through summer and autumn to minimums of 1.6-1.9 m/s in July 2012 (Figure 3.7). The monthly averaged mean daily wind run increased from a minimum of 138 km/d at PF to a maximum of 306 km/d at LDF. Daily wind run ranged from 79-801 km/d at LDF, 77-729 km/d at TSD and 28-677 km/d at PF.
Figure 3.6  Mean daily relative humidity, by month, at Larundel Dairy Farm (▲), Three Springs Dairies (●) and Pendo Farms (●) for September 2011 to September 2012. Data were sourced from the NIWA on-site meteorological stations 39224, 37920 and 38866.

Figure 3.7  Mean daily wind speed (left) and wind run (right), by month, at Larundel Dairy Farm (▲), Three Springs Dairies (●) and Pendo Farms (●) for September 2011 to September 2012. Data were sourced from the NIWA on-site meteorological stations 39224, 37920 and 38866. Measurements of wind speed were taken at 2.5 m above ground level.

3.2.4 Experimental design

Data presented in this chapter and Chapter 4 were collected as part of the MBIE Waterscape Programme (Section 1.4). Accordingly, the experimental design at each site was not exclusive to the research of this thesis, and much of the data, while collected for this thesis, have been available for other purposes.

Three 500 mm diameter, 700 mm deep drainage lysimeters were installed by Aqualinc Research Limited at each of the three experimental sites during 2010 and 2011 as part of the Waterscape Programme. For this study, the lysimeters have been identified as L1, L2, and L3 at each site, denoting
Lysimeter 1, Lysimeter 2, and Lysimeter 3, respectively. A description of the lysimeter installations is
given in Chapter 4 (Section 4.2.1.1).

The experimental design of the project assumed that pasture management at all sites was the same,
for example, growing well-watered, fertilised, perennial ryegrass/white clover pasture under a
rotational dairy grazing system (Sections 3.2.4.1 to 3.2.4.4). Therefore, any differences among the sites
were not expected to be critical in controlling differences in water use among sites. Accordingly,
pasture canopy observations and measurements were undertaken at the LDF site only. Measured
herbage yield and growth rates at LDF were then used to calibrate the pasture growth model
‘DairyMod’, with which pasture growth in the lysimeters at the Three Springs Dairies and Pendo Farms
sites was quantified.

Three locations at LDF were included in the pasture sampling, with three replicates at each location.
However, these were not true replicates, as they could not be randomly assigned. Therefore, the goal
of having three of each was to enable the most accurate measurements of pasture yield and canopy
to be obtained. Pasture measurements were carried out from each of the three lysimeters, from five
(1.0 m x 0.5 m) cages placed in the wider paddock, and from an area designated ‘channels’ which
consisted of three aluminium channels (800 x 25 x 10 mm (L x W x H)) installed at ground level in the
pasture. The cages remained in place throughout the grazing season. Outside of the grazing season,
the cages were relocated after each harvest. The purpose of the channels was to enable leaf area and
canopy light interception measurements from ground level (Plate 3.4).

![Plate 3.4 Channel installation at ground level at Larundel Dairy Farm, prior to canopy
reestablishment (a). Illustration of canopy leaf area and light interception measurement
within installed channel at Larundel Dairy Farm (b).](image)

For this study, the channels have been identified as C1, C2 and C3, in reference to Channel 1, Channel
2, and Channel 3, respectively. The lysimeters and channels were fenced off from stock to prevent
grazing of the pasture. Figure 3.8 illustrates the locations and positioning of the channels and cages
with respect to the lysimeters at LDF. A description of the pasture sampling methods used is given in Section 3.2.5.

![Diagram](image)

Figure 3.8 Layout of the cages, channels and lysimeters for pasture canopy sampling and measurements at Larundel Dairy Farm. Not to scale.

### 3.2.4.1 Pasture

At each of the three experimental sites, the pasture consisted of a perennial ryegrass/white clover mix sown in 2000 at LDF, 2006 at TSD and 2001 at PF. However, clover growth was observed to be suppressed by clover root weevil (*Sitona lepidus*) at LDF (B. McKercher, pers. comm., 4 Dec. 2012).

### 3.2.4.2 Stock/graazing management

Up to 1,600 cows were milked twice daily for ~300 days per year between August and May on the ~370 ha LDF property, giving a peak stocking rate of ~4 cows/ha. The pasture in the lysimeter paddock was grazed over a 2-4 day period to a residual of 50-60 mm, initiated once the ryegrass pasture had formed three new leaves per tiller. Sampling of the pasture was typically carried out within 24 hours of the end of each grazing to mimic the grazing schedule. Table 3.6 provides details of the number and duration of each regrowth cycle at LDF. The experiment was conducted over a one-year period from 09/09/2011 through to 07/09/2012. At the beginning of the experiment (09/09/2011), which coincided with the end of the first grazing of the season, the pasture in each of the cages, channels and lysimeters was clipped to a height of 60 mm.
Table 3.6  Regrowth cycles, start and end dates from 09/09/2011 to 07/09/2012.

<table>
<thead>
<tr>
<th>Regrowth cycle</th>
<th>Start date</th>
<th>End date</th>
<th>Regrowth duration (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>25/11/2011</td>
<td>17/12/2011</td>
<td>22</td>
</tr>
<tr>
<td>4</td>
<td>18/12/2011</td>
<td>9/01/2012</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>10/01/2012</td>
<td>30/01/2012</td>
<td>20</td>
</tr>
<tr>
<td>6</td>
<td>31/01/2012</td>
<td>20/02/2012</td>
<td>20</td>
</tr>
<tr>
<td>7</td>
<td>21/02/2012</td>
<td>21/03/2012</td>
<td>29</td>
</tr>
<tr>
<td>8</td>
<td>22/03/2012</td>
<td>4/05/2012</td>
<td>43</td>
</tr>
<tr>
<td>9</td>
<td>5/05/2012</td>
<td>7/09/2012</td>
<td>125</td>
</tr>
</tbody>
</table>

Note 1: End date indicates the date pasture was clipped and was within 24 hours of the end of stock grazing.
Note 2: Pasture spelted for 53 days to be harvested for silage.

TSD (~330 ha) and PF (~206 ha) milked up to 1,200 and 880 cows, respectively, twice daily for ~300 days per year between August and May. Peak stocking rates were therefore 3.6 and 4.3 cows/ha, respectively. Actual grazing dates at TSD and PF are unknown. Liaison with farm management indicated grazing at TSD was triggered at the three-leaf stage, equating to 5-6 week cycles during the shoulder months of the season (September-October, March-May) and 3-4 week cycles during the peak of the season (November-February). At PF, grazing occurred on a strict 16-day cycle from September to May.

3.2.4.3 Irrigation
At the three sites centre pivots were used to irrigate the pasture from approximately September to April. Irrigation water was sourced from groundwater at each of the three experimental sites, as well as from Waimakariri Irrigation Scheme at LDF. Section 3.2.3.1 provided a summary of the irrigation applied at each experimental site over the 2011/12 irrigation season.

3.2.4.4 Nitrogen
At LDF, nitrogen (N) fertiliser was applied to the experimental site immediately following each grazing. Fertiliser was applied in the form of Urea (46% N) at a rate of 23 kg N/ha per application (B. McKercher, pers. comm., 4 Dec. 2012). In total there were 9 x 23 kg N/ha applications over the experimental period, totalling 207 kg N/ha. At TSD and PF, 170 kg N/ha (C Mackenzie, pers. comm., 27 Jun. 2012) and 208 kg N/ha (W. Leferink, pers. comm., 4 Feb. 2013) were applied over the experimental period, respectively. However, actual application rates and dates are unknown.

3.2.5 Measurements
3.2.5.1 Dry matter production
Herbage mass (HM, kg DM/ha) was measured at LDF at the end of each regrowth cycle by clipping the pasture covering the 0.2 m² lysimeters and the pasture within a 0.2 m² quadrat area over the channels
and within the cages using grass shears. Herbage mass was also measured twice within each regrowth cycle in the cages. The pasture was clipped to a residual height of ~60 mm to reflect the grazed height of the surrounding pasture. Twelve additional pasture cuts were taken following clipping of the pasture during August 2012 to establish the residual herbage mass, which gave a mean herbage residual of ~1.0 t DM/ha (not shown). The cut pasture samples were oven dried at 65°C for a minimum of 48 hours then weighed. The herbage mass of each quadrat was determined as follows:

\[
\text{HM (kg DM/ha)} = \frac{\text{total quadrat sample dry weight (g)}}{0.20 \text{m}^2 \times 10^3.3}
\]

A Jenquip rising plate meter (RPM), which measures the compressed height of the pasture, taking into account variations in the pasture density ( Trafford & Trafford, 2011), was used to indirectly measure the changes in herbage mass of the pasture in the channels and lysimeters within each regrowth cycle. An average of four plate meter readings were recorded within each cage and channel quadrat and each lysimeter at the end of each regrowth cycle and twice within each regrowth cycle. Calibration of the plate meter was achieved by pairing the averaged RPM readings to measurements of herbage mass. Linear regression was used to determine the calibration equations (Section 3.2.7.1). The within regrowth cycle RPM readings for the lysimeters and channels were converted to herbage mass using the derived seasonal calibration equations.

The total yield (TY, kg DM/ha) for each regrowth cycle was taken to be equal to the herbage mass destructively measured at the end of each cycle.

Prior to drying, representative sub-samples were manually separated from the clipped end of regrowth cycle pasture and sorted into grass, clover, weed and dead material to determine the botanical composition by dry weight. Representative sub-samples of the within regrowth cycle cut samples from the cages were separated into dead and green material.

\subsection*{3.2.5.2 Sward height}

In addition to RPM readings, pasture height was measured using a ruler at the end of each regrowth cycle and twice within each regrowth cycle. Within each channel and cage quadrat and each lysimeter a minimum of five undisturbed sward height measurements were taken and an average of the measurements recorded.

Daily pasture height values were determined by assuming a linear increase in height between measurements. Following each end of regrowth cycle sampling, pasture height was on average 60 mm.

\subsection*{3.2.5.3 Light interception and pasture leaf area}

An AccuPAR LP-80 ceptometer was used to non-destructively measure the pasture canopy PAR interception and LAI (LAI\text{cept}) above ground level. PAR interception measurements were taken during each end of the regrowth cycle and within regrowth cycle sampling events in the channels. LAI\text{cept} was
recorded on 10 occasions, including during November 2011 and then again from May to August 2011. Twelve pre- and post-clipping above and below canopy PAR and LAI<sub>cept</sub> measurements were taken from the wider paddock area over two visits to the site during August 2012 due to a previously limited number of recorded LAI<sub>cept</sub> measurements. This enabled a full spectrum of results to be obtained and allowed residual LAI<sub>cept</sub> values to be determined.

LAI<sub>cept</sub> values could not be directly determined for the lysimeters as rubber rims around the top of the lysimeters (Section 4.2.1.1) made it physically impossible. In addition, installation of channels in the lysimeters would have adversely affected their operation. Therefore, prior to drying, the green leaf area of the botanically separated clipped pasture samples from the lysimeters and channels (Section 3.2.5.1) were measured using a LI-COR LI-3100C leaf area meter. The green area index (GAI), taken to be the ratio of leaf green area to the 0.2 m<sup>2</sup> quadrat/lysimeter area, was determined by dividing the green leaf area of the total clipped pasture sample by the quadrat area. The GAI values differed from the LAI<sub>cept</sub> values because they were for the green material only and related to the leaf area of the pasture above the residual cut pasture height of 60 mm. The LAI<sub>cept</sub> values were taken from ground level and included dead material.

LAI<sub>cept</sub> measurements were paired with corresponding GAI values from the channels and linear regression used to determine the calibration equation. Lysimeter LAI<sub>cept</sub> values were estimated by applying the calibration equation to the lysimeter GAI measurements. Daily LAI<sub>cept</sub> values for the lysimeters were estimated by assuming LAI<sub>cept</sub> increased linearly between consecutive measurements. A LAI<sub>cept</sub> value of 0.6 was assumed immediately following grazing based on averaged post-clipping measurements. A value of 0.6 is typical of a hard grazed system (Korte <i>et al.</i>, 1984).

For clarification purposes, LAI and GAI have been defined throughout the remainder of this thesis as follows:

- **LAI** refers to the total one-sided leaf area of the pasture above ground level per unit of soil below it, and is expressed as the m<sup>2</sup> leaf area per m<sup>2</sup> of ground area.

- **GAI** refers to the one-sided leaf area of the pasture above the residual grazed/cut height of the pasture, and includes only the live (green) material. The GAI is expressed as the m<sup>2</sup> green leaf area per m<sup>2</sup> of ground area.

### 3.2.5.4 Herbage nitrogen

Sub-samples taken from the dried end of regrowth cycle pasture samples were analysed to determine the nitrogen concentration (N%) of the pasture grown in the lysimeters and cages. The samples were ground using a Retsch ZM 200 Rotor Mill with a 1 mm sieve, and tested for N% using near-infrared spectroscopy (NIR) at the Lincoln University analytical laboratory.
3.2.6 Pasture growth modelling

3.2.6.1 Larundel Dairy Farm

DairyMod (Johnson et al., 2008) (version 5.3.13) (Section 2.3.2.6) was used to model lysimeter-measured ryegrass/white clover pasture growth at LDF, West Eyreton, Canterbury. The model was calibrated using the average measured herbage yield data from the lysimeters at LDF. Once calibrated, the model was used to predict pasture growth (daily and total yields and daily pasture LAI and height) from the TSD and PF lysimeters. Validation of DairyMod is carried out with an independent data set in Chapter 5.

At LDF, single paddock simulations were run over a 10-year period (2003-2013), although only data from September 2011- September 2012 was used, in line with that measured. Simulations were run with 10 ‘loops’ to reduce the influence of the initial conditions (Johnson, 2013b). Parameters were set within the management module of the model, which describes stocking rates, grazing management, fertilisation and irrigation, to replicate the management of the pasture at LDF. For example, set grazing dates were used over the experimental period (Table 3.6). Daily climate data inputs of air temperature, solar radiation, wind speed, vapour pressure and precipitation were sourced from the on-site meteorological station (Section 3.2.3). Irrigation applied to the lysimeters (Figure 3.2) was added to the daily rainfall totals. Nitrogen fertiliser was applied immediately following each grazing at a rate of 23 kg N/ha (Section 3.2.4.4). Stocking rates were set so that the pasture was grazed to a residual of 1.0 t DM/ha during each grazing event, excluding the initial grazing (09/09/2011) where a residual of 1.5 t DM/ha was applied. The value of 1.0 t DM/ha was based on post-grazing/clipping measurements taken at the experiment site (Section 3.2.5.1).

Within the biophysics water module, soil hydraulic and physical properties are defined. DairyMod allows three soil layers to be specified, with each rounded to the nearest 100 mm. The soil layers were therefore set from 0-200 mm, 200-500 mm and 500-700 mm based on the lysimeter soil description profile depths (Table 3.2). Field capacity and wilting point values were determined from the soil water retention curve data for LDF (Table 3.2) at soil water potentials of -10 kPa and -1,500 kPa (McLaren & Cameron, 1996). The saturated ($\theta_s$) and air dry water contents ($\theta_d$) and saturated hydraulic conductivity ($K_{sat}$) values were those used and tested in the HYDRUS simulations based on paired matric potential and soil water content measurements made on-site (Section 4.2.4.1 in Chapter 4). The clay percentage of the soil included in the model was taken from the site soil descriptions provided in Appendix 1. Table 3.7 provides a summary of the soil physical parameters used. Other than for the parameters specified in Table 3.7, default values within the model were assumed. A ‘medium’ organic matter soil, for which the model default values were maintained, was also assumed.
Table 3.7  Soil hydraulic property values set for DairyMod pasture growth simulations of lysimeter-grown perennial ryegrass-based pasture at Larundel Dairy Farm, Canterbury.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Depth (mm)</th>
<th>$K_{sat}$ (mm/d)</th>
<th>$\theta_{s}$ (% volume)</th>
<th>$\theta_{r}$ (% volume)</th>
<th>$\theta_{fc}$ (% volume)</th>
<th>$\theta_{wp}$ (% volume)</th>
<th>Clay content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-200</td>
<td>175</td>
<td>43</td>
<td>0</td>
<td>39</td>
<td>19</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>200-500</td>
<td>77</td>
<td>31</td>
<td>0</td>
<td>23</td>
<td>13</td>
<td>30</td>
</tr>
<tr>
<td>3</td>
<td>500-700</td>
<td>2,002</td>
<td>18</td>
<td>2</td>
<td>8</td>
<td>3</td>
<td>10</td>
</tr>
</tbody>
</table>

$\theta_{s}$ and $\theta_{r}$ are the saturated and air dry water contents, $K_{sat}$ the saturated soil hydraulic conductivity, $\theta_{fc}$ field capacity and $\theta_{wp}$ the wilting point.
Clay content (%) is in reference to the stone free fraction of the soil.

Sensitivity analysis overview

Within the biophysical pasture module, the pasture sward is described. Default parameters are given, for example, describing the pasture structure, photosynthesis, and effects of water and temperature on growth of various pastures (Section 2.3.2.6).

At LDF, default values within the pasture module were initially assumed for perennial ryegrass and white clover. However, White et al. (2008) reported improved model performance in Canterbury with rooting depths and temperature parameters (i.e. high and low initial, full and recovery temperature stress values and optimum and minimum temperatures for light-saturated leaf gross photosynthesis) modified from the model default values (Table 2.1). Accordingly, a sensitivity analysis was performed on each of the temperature parameters at Larundel Dairy Farm, as well as the pasture composition (Table 3.8). For example, clover root weevil inhibited clover growth at LDF (Sections 3.2.4.1 and 3.3.4); therefore, the effect of including and excluding white clover from the simulations was tested. The model dictated the change increments able to be applied to each of the parameters tested.

The range tested for each of the parameters was based on a combination of the model default values, values reported in the literature and iterative adjustment of the parameters sufficient to allow a trend to be identified.

A default rooting depth of 400 mm is given for ryegrass pasture in the model. Garwood and Sinclair (1979) reported an effective water abstraction depth of 800 mm for a perennial ryegrass pasture, which compares with a depths of 40-1100 mm reported by Parry et al. (1992) and McKenzie et al. (1990). However, deeper-rooted pastures are often associated with dryland environments subjected to water stress (White & Snow, 2012). Rooting depths of up to 700 mm were tested, corresponding to the maximum rooting depth allowed for by the lysimeters (Table 3.8).

Cumulative temperature stress functions have been included in the DairyMod model to account for the effects of temperature extremes on photosynthetic capacity (Johnson, 2013a) (Section 2.3.2.6). As a default in the model, however, the high and low temperature stress functions for C₃ crops are not implemented. When implemented, the model gives default temperature stress values, the adjustment
of which has been found to improve pasture growth predictions by White et al. (2008) and Cullen et al. (2008) (Table 2.1). For the current sensitivity analysis, both activated and inactive temperature stress were tested. When activated, the temperature stress ranges given in Table 3.8 were tested.

Default minimum and optimum temperatures for $P_m$ of 3 and 23°C, respectively, have been specified in the model (Section 2.3.2.6). Minimum and optimum temperatures have been reported throughout the literature to range from 0-6°C and 19-29°C, respectively (Section 2.3.2.3), however optimum values of 0-23°C are more typical and have therefore been included in the sensitivity analysis (Table 3.8).

The sensitivity process involved manually altering a single parameter while all others were held constant, and iteratively running simulations. Following each simulation run, simulated herbage yields were statistically compared with the observed lysimeter herbage yields using NSE coefficient and NRMSD (Section 2.5). For each tested parameter, the value that gave the highest NSE coefficient and lowest NRMSD was selected. Where the default model value gave the closest fit with the observed data, the default value was maintained (Table 3.8 and Appendix 5). It is recognised that such a process is likely to give a local rather than global optimum. However, the model prevents systematic variation of all parameters to seek a global ‘best’ combination.

Table 3.8  Sensitivity analysis comparing pasture composition (+/- white clover), pasture rooting depths and temperature and stress functions in DairyMod pasture growth simulations for lysimeter-grown perennial ryegrass-based pasture at Larundel Dairy Farm (LDF), Canterbury. Selected values are those used to model pasture growth at LDF in Section 3.3.8.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Model default</th>
<th>Range tested</th>
<th>Change increments</th>
<th>NSE range</th>
<th>NRMSD</th>
<th>Value selected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pasture composition - clover</td>
<td>n/a</td>
<td>True/False</td>
<td>-</td>
<td>0.37-0.42</td>
<td>0.61-0.64</td>
<td>FALSE</td>
</tr>
<tr>
<td>Ryegrass rooting depth (mm)</td>
<td>400</td>
<td>300-700</td>
<td>100</td>
<td>0.40-0.42</td>
<td>0.61-0.62</td>
<td>400</td>
</tr>
<tr>
<td>Temperature stress ryegrass (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No stress</td>
<td>TRUE</td>
<td>-</td>
<td>-</td>
<td>0.28</td>
<td>0.68</td>
<td>FALSE</td>
</tr>
<tr>
<td>Low, initial stress</td>
<td>5</td>
<td>-4-5</td>
<td>1</td>
<td>-0.79-0.60</td>
<td>0.51-1.08</td>
<td>-1</td>
</tr>
<tr>
<td>Low, full stress</td>
<td>-1</td>
<td>-10-0</td>
<td>1</td>
<td>-1.10-0.79</td>
<td>1.08-1.17</td>
<td>-5</td>
</tr>
<tr>
<td>Low, recovery sum</td>
<td>100</td>
<td>50-140</td>
<td>10</td>
<td>0.56-0.62</td>
<td>0.50-0.54</td>
<td>130</td>
</tr>
<tr>
<td>High, initial stress</td>
<td>30</td>
<td>24-30</td>
<td>1</td>
<td>0.62-0.70</td>
<td>0.44-0.49</td>
<td>24</td>
</tr>
<tr>
<td>High, full stress</td>
<td>35</td>
<td>25-32</td>
<td>1</td>
<td>0.69-0.82</td>
<td>0.34-0.45</td>
<td>25</td>
</tr>
<tr>
<td>High, recovery sum</td>
<td>100</td>
<td>0-60</td>
<td>10</td>
<td>0.74-0.82</td>
<td>0.34-0.41</td>
<td>40</td>
</tr>
<tr>
<td>Maximum photosynthesis ryegrass (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum temperature</td>
<td>3</td>
<td>2.5-4.5</td>
<td>0.5</td>
<td>0.78-0.85</td>
<td>0.31-0.38</td>
<td>4.5</td>
</tr>
<tr>
<td>Optimum temperature</td>
<td>23</td>
<td>19-23</td>
<td>1</td>
<td>0.73-0.82</td>
<td>0.34-0.39</td>
<td>23</td>
</tr>
</tbody>
</table>

Note: NSE is the Nash-Sutcliffe efficiency and NRMSD the root mean square deviation, normalised to the mean of the observed data, used to statistically compare the simulated and observed herbage yields.
Results of the sensitivity analysis at LDF

NSE values of <0.85 were achieved (Table 3.8, Appendix 5). Excluding clover from the simulations gave a slightly higher NSE (0.42) and lower NRMSD (0.61) than when clover was included (NSE=0.37, NRMSD=0.64). Maintaining the model default rooting depth of 400 mm also gave the highest NSE (0.42) and lowest NRMSD (0.61) compared with any other rooting depth or transpiration stress coefficient. When temperature stress was initiated, NSE coefficients increased and NRMSD values decreased. Iterative adjustment of the low and high initial, full and temperature sum recovery values increased the NSE values to 0.82 and reduced the NRMSD to 0.34. Minimum and optimum temperatures for photosynthesis of 4.5°C and 23°C resulted in the highest NSE (0.85) and lowest NRMSD (0.31). According to Peri et al. (2002b), the optimum temperature range for a cocksfoot pasture in Canterbury is 19-23°C, above which the photosynthetic rate declines by 0.077 units per °C from 23-31°C. This supports an optimum value of 23°C and initial high stress temperature of 24°C, but a full temperature stress value of 25°C is biologically unlikely. Rather full temperature stress should be in the range of 29-31°C, as reported by White et al. (2008). However, the value of 25°C has been maintained in order to achieve a reasonable fit between the observed and simulated herbage production at LDF, which is required for simulating canopy LAI and height in the PETc modelling in Chapter 4.

Height calculations

Sward height is not given as a direct output from the model, but it can be calculated from the relationship between canopy LAI and height defined by a non-rectangular hyperbola (Johnson, 2013a), which can be written as:

$$h = \frac{1}{2\xi}\left[\alpha LAI + h_m - \{(\alpha LAI + h_m)^2 - 4\alpha \xi h_m LAI\}^{1/2}\right]$$  \hspace{1cm} 3.4

$$\alpha = h_m \frac{(2-\xi)}{2LAI_{half}}$$ \hspace{1cm} 3.5

$$\xi = 0.9$$ \hspace{1cm} 3.6

where \(\alpha\) is the initial slope of the response, \(h_m\) the asymptote or maximum canopy height, \(\xi\) curvature parameter and \(LAI_{half}\) is the LAI at half the maximum height. DairyMod defaults the maximum height of perennial ryegrass to 500 mm. At 250 mm, the LAI of the pasture at LDF was approximately four (not shown).

3.2.6.2 Three Springs Dairies and Pendo Farms

Once calibrated against the observed LDF lysimeter herbage growth, DairyMod was used to estimate herbage yields at TSD and PF to enable a comparison with that observed at LDF, and to provide daily LAI and pasture height data for estimating evapotranspiration over the experimental period (Chapter 4).
Simulations were run from 2003-2013, with 10 loops. Daily climate data inputs of air temperature, solar radiation, wind speed, vapour pressure and precipitation were sourced from the on-site meteorological stations (Section 3.2.3). Irrigation applied to the lysimeters (Section 3.2.4.3) was added to the daily rainfall totals. Grazing was described within the model from information provided by the farm managers at TSD and PF (Section 3.2.4.2). The pasture was assumed to be grazed to a residual of 1.0 t DM/ha, excluding the initial grazing of the season where a residual of 1.5 t DM/ha was applied, as at LDF. Application of N fertiliser was assumed to occur following each grazing and was determined by dividing the total nitrogen applied, being 170 and 208 kg N/ha/y for TSD and PF, respectively (Section 3.2.4.4), by the number of grazing events over the season.

For the perennial ryegrass component, the same rooting depths and temperature and transpiration stress functions used in the calibrated model were applied (Table 3.8). Appropriate stress functions for white clover in Canterbury were tested by White et al. (2008) (Table 2.1) and were applied at TSD and PF. Table 3.9 provides a summary of the pasture values used in the simulations at TSD and PF.

Within the biophysics water module the soil layers, rounded to the nearest 100 mm, were set to 0-300, 300-500 and 500-700 mm at TSD and to 0-200, 200-400 and 400-700 m at PF, based on the soil profile descriptions given in Section 3.2.2 and Appendices 2 and 3. FC and WP values for each layer were estimated from the soil water retention curve data (Section 4.2.4.2). The saturated (θₜ) and air dry water contents (θₑ) and saturated hydraulic conductivity (Kₘ) values were those used and tested in the HYDRUS simulations (Section 4.2.4.2). The soil clay content was based on the soil descriptions provided in Appendices 2 and 3. Table 3.10 provides a summary of the soil physical parameters assumed for TSD and PF.

Table 3.9 Pasture growth parameter settings used in DairyMod simulations for lysimeter-grown perennial ryegrass/white clover pastures at Three Springs Dairies, Methven and Pendo Farms, Dorie in Canterbury.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Perennial ryegrass</th>
<th>White clover</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-grazing herbage residual (t DM/ha)</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Rooting depth (mm)</td>
<td>400</td>
<td>300</td>
</tr>
<tr>
<td>Temperature stress (°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, initial stress</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>Low, full stress</td>
<td>-5</td>
<td>-2</td>
</tr>
<tr>
<td>Low, temperature sum for recovery</td>
<td>130</td>
<td>30</td>
</tr>
<tr>
<td>High, initial stress</td>
<td>24</td>
<td>30</td>
</tr>
<tr>
<td>High, full stress</td>
<td>25</td>
<td>35</td>
</tr>
<tr>
<td>High, temperature sum for recovery</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Photosynthesis (°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum temperature</td>
<td>4.5</td>
<td>3</td>
</tr>
<tr>
<td>Optimum temperature</td>
<td>23</td>
<td>23</td>
</tr>
</tbody>
</table>
Table 3.10  Soil hydraulic property values used in DairyMod pasture growth simulations for lysimeter-grown perennial ryegrass/white clover pastures at Three Springs Dairies (TSD) and Pendo Farms (PF), Canterbury.

<table>
<thead>
<tr>
<th>Site</th>
<th>Soil layer</th>
<th>Depth (mm)</th>
<th>Ksat (mm/d)</th>
<th>ϑs (%volume)</th>
<th>ϑt (%volume)</th>
<th>ϑfc (%volume)</th>
<th>ϑwp (%volume)</th>
<th>Clay content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-300</td>
<td>5613</td>
<td>36.1</td>
<td>3.1</td>
<td>35.0</td>
<td>19.2</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>TSD</td>
<td>2</td>
<td>300-500</td>
<td>2342</td>
<td>30.8</td>
<td>1.8</td>
<td>30.0</td>
<td>14.7</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>500-700</td>
<td>12103</td>
<td>14.7</td>
<td>3.6</td>
<td>13.7</td>
<td>4.8</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0-200</td>
<td>5357</td>
<td>41</td>
<td>0.0</td>
<td>35.8</td>
<td>17.6</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>PF</td>
<td>2</td>
<td>200-400</td>
<td>346</td>
<td>43.7</td>
<td>0.0</td>
<td>30.5</td>
<td>17.4</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>400-700</td>
<td>85</td>
<td>44.5</td>
<td>0.5</td>
<td>34.1</td>
<td>15.2</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

ϑs and ϑt are the saturated and air dry water contents, Ksat the saturated soil hydraulic conductivity, ϑfc field capacity and ϑwp the wilting point.

Clay content (%) is in reference to the stone free fraction of the soil.

3.2.7 Calculations

3.2.7.1 Herbage mass

Where herbage mass was not directly measured for the lysimeters and channels within each regrowth cycle at LDF, herbage mass was estimated from the calibration of herbage mass with RPM data.

Linear regression analyses of measured herbage mass (above the residual grazing height) and RPM readings from the cages and each of the lysimeters and channels were undertaken on a seasonal basis. Conventional calendar seasons were used. Summer refers to the months December-February, autumn the months March-May, winter the months June-August, and spring the months September-November.

Two-tailed t-tests were performed on the slopes of the regressions within each season. The t-tests found no differences in the slopes of the regressions (α=0.05), except for L1, which behaved differently, probably due to a greater flat weed (dandelion, Taraxacum officinale) component that reduced grass growth (Section 3.3.4). Where the results for L1 were excluded, coefficients of determination were greatest in spring, summer and autumn at 0.84-0.95 compared with 0.84-0.92, and a single regression for each season was possible (Figure 3.9). The winter regression relates only to pasture measurements from the cages as no grazing occurred, and therefore no herbage mass measurements were taken from the lysimeters or channels. A summary of the seasonal regressions is given in Appendix 6. Figure 3.9 gives the final coefficients of calibration equations that were used to estimate herbage mass in the lysimeters and channels within each regrowth cycle where direct measurements were not possible. The regression x-axis intercepts of ~3 cm, on average, represented the residual grazing height of the pasture (Section 3.3.5).
Figure 3.9  Seasonal herbage mass and rising plate meter (RPM) height regressions for perennial ryegrass from lysimeter (▲), channel (■) and cage (◆) measurements at Larundel Dairy Farm for the period 09/09/11-07/09/2012. Measurements for L1 are shown (△) but were not included in the regressions. Forms of the fitted lines are spring: $y = (228\pm9.5)x - (782\pm109.0)$ ($r^2=0.95$); summer: $y = (150\pm8.7)x - (362\pm67.5)$ ($r^2=0.84$); autumn: $y = (150\pm10.4)x - (374\pm90.2)$ ($r^2=0.89$); and winter: $y = (94\pm8.3)x + (135\pm38.8)$ ($r^2=0.88$).

3.2.7.2  Thermal time

Thermal time (T_t) was calculated using the method provided by Jones and Kiniry (1986), for which a sinusoidal function is fitted to mean daily air temperature, where it exceeds $T_b$ (Section 2.3.2.3 and Equation 2.3). Air temperature data were recorded on-site at LDF throughout the study period at 10-minute intervals (Section 3.2.3.2). T_t was therefore calculated every 10 minutes and summed to give daily values.

To determine the most appropriate $T_b$ value for this research, linear regression analysis of accumulated herbage mass against accumulated T_t over the 2011/12 growing season was undertaken for each of the channels and lysimeters and for the cages, for a range of base temperatures. $T_b$ values of 0-8°C were compared, based on the findings of Mills (2007), Moot et al. (2000), and Tonmukayakul (2009) (Section 2.3.2.3). A graph showing the resultant $r^2$ values against $T_b$ for the lysimeters, channels and
cages is given as Figure 3.10. At all locations, \( r^2 \) values were high for each \( T_b \) value tested, with a range of 0.986-0.997. A value of 3°C was selected and used in the analysis of \( T_t \) pasture growth to be consistent with previous studies (Section 2.3.2.3). An optimum growth temperature of 23°C was used, as reported by Peri et al. (2002b) and used in the DairyMod modelling (Section 3.2.6.1).

Temperature adjusted growth rates (TAGR) were determined from the slope of the relationship between accumulated total herbage yield and accumulated \( T_t \).

![Graph showing \( r^2 \) values against \( T_t \) base temperature]

**Figure 3.10** Coefficients of determination \((r^2)\) from regressions of accumulated herbage mass against accumulated thermal time \((T_t)\), using a range \((0-8^\circ C)\) of base temperatures for ryegrass pasture at Larundel Dairy Farm in the cages (●), lysimeters L1 (■), L2 (○), and L3 (▲), and channels C1 (■), C2 (○), and C3 (▲), for the period 09/09/2011 to 04/05/2012.

### 3.2.7.3 Nitrogen Nutrition Index (NNI)

The nitrogen status of the pasture was determined by deriving the NNI using Equations 2.4 and 2.5. For this study, the herbage dry matter component was the accumulated dry matter above the residual grazing height of 60 mm between each grazing event, from which \( N_{\text{act}} \) was measured.

### 3.2.8 Statistical analysis

Statistical analysis of the data was conducted in GenStat (version 17, VSN International Ltd, 2013).

An unrepresentatively high flat weed component in L1 led to anomalies when the herbage mass, pasture height, leaf area and botanical composition data were analysed. Accordingly, data collected from L1 were replaced with ‘missing values’ in the analysis, but the observed data have been presented separately in the results figures for illustrative purposes.

Annual total herbage yields, mean daily growth rates over each regrowth cycle, herbage height and herbage nitrogen content were analysed using one-way ANOVA procedures in randomised blocks, with
site (i.e. lysimeter, cage and channel) as the treatment effect. Differences among sites (annually and seasonally) and seasons in the botanical composition of the pasture were also tested using ANOVA procedures. Where treatment means were significant (α=0.05), they were separated using Fisher’s protected least significant difference (LSD) tests. Unless otherwise specified, standard errors of the mean (SEM) were used to describe variation in the data within treatments.

A split-line regression model was fitted to the herbage yield and Tt data for each of the lysimeters, channels and cages to quantify the TAGRs (slopes of the fitted relationships), and when they changed throughout the year. Simple linear regression analysis was used to estimate average annual TAGRs. The TAGRs were analysed using ANOVA procedures to determine any differences among sites.

Regression analysis was used to determine relationships between channel-based measurements of LAI_{opt}, GAI and PAR interception. One-way ANOVA procedures were used to test for differences in the channel and lysimeter GAI measurements.

The ability of DairyMod to predict pasture growth was tested by comparison of simulated and observed herbage yields at the end of each regrowth cycle and accumulated over the experiment. To determine the accuracy of the predictions the Nash-Sutcliffe coefficient of efficiency (NSE) and the root mean square error, normalised to the observed mean (NRMSD), were calculated according to the methods detailed in Section 2.5.

To gain further insight into causes of model deviations, the MSD, being the RMSD squared, values were partitioned into the squared bias (SB), non-unit slope (NU) and lack of correlation (LC), as given by Equations 2.58-2.61.

Where data are presented in tables, italicised font has been used to distinguish simulated results from measured data, for which normal font has been maintained.
3.3 Results

3.3.1 Herbage dry matter production

Total herbage dry matter production over the experimental period was similar (P=0.153) for the lysimeters, channels and cages at 10.8±0.88 t DM/ha (Figure 3.11). The ANOVA that compared accumulating herbage mass at the end of each regrowth cycle also identified no differences (0.153<P<0.341) among the lysimeters, channels and cages. For example, between 09/09/2011 and 01/11/2011, the lysimeters, cages and channels produced 3.5±0.51 kg DM/ha (P=0.286).

![Figure 3.11: Accumulated herbage yield of perennial ryegrass/white clover pasture for the lysimeters (▲), channels (■), and cages (✦) at Larundel Dairy Farm, Canterbury, for the period 09/09/2011 - 07/09/2012. Treatment means for the lysimeters excluded L1 (△). The error bar shows the standard error of the mean for the total herbage yield.]

3.3.2 Mean daily herbage growth rates

There were no differences (0.085<P<0.840) in growth rates among the lysimeters, channels and cages over the study period, except for the regrowth cycle ending 04/05/2012 (Regrowth 8). During Regrowth 8, the growth in the cages was greater (P=0.027) at 25.1 kg DM/ha/d compared with 14.7±1.55 kg DM/ha/d in the channels and lysimeters (Figure 3.12).

Mean daily herbage growth rates (HGR) of the pasture showed seasonal variation, whereby rates of up to 69.0±4.8 kg DM/ha/d were achieved in early spring, compared with 6.5±0.88 kg DM/ha/d through the winter (Figure 3.12). The peak in growth rates during spring caused rapid increases in herbage mass from early October to early November (Figure 3.11), which was followed by a summer slump. Between 09/09/2011 and 01/11/2011, the pasture was spelled for seven weeks before being harvested for silage. This resulted in seed head development and associated increases in herbage mass and calculated pasture growth rates. Management of smaller areas, such as the cages, lysimeters and channels for silage is difficult, and the presence or absence of a few seed heads can make a big
difference in herbage mass measurements. The data also indicate that the pasture was not grazed as hard during the first season grazing on 09/09/2011, resulting in a starting residual greater than the 1.0 t DM/ha that was applied to the remainder of the season (Section 3.2.5.1). The results of pasture growth modelling in Section 3.3.8 suggest a residual of ~1.5 t DM/ha was more likely. From November 2011 through to March 2012, growth rates among sites remained relatively constant between 30-50 kg DM/ha/d. Full details of the HGR for each regrowth cycle, with site effects, are given in Appendix 7.

![Graph showing mean pasture growth rates](image)

Figure 3.12 Lysimeter (▲), channel (■) and cage (♦) mean daily herbage growth rates of perennial ryegrass-based pasture at Larundel Dairy Farm, Canterbury, for the period 09/09/2011-07/09/2012. Each point represents the mean daily growth rate over a full regrowth cycle. Treatment means for the lysimeters excluded L1 (△). The error bar (to the right) shows the maximum standard error of the mean for the regrowth cycle ending 04/05/2012 (Regrowth 8), where the effects of site were significant (P=0.027).

### 3.3.3 Temperature adjusted growth rates

Accumulated herbage yields in the cages, channels, and lysimeters were related to Tt to assess pasture growth without the influence of temperature (Figure 3.13). For all sites, the relationship between accumulated herbage yield and Tt was linear up until April/May 2012, at which point the TAGR reduced (Table 3.11, Figure 3.13). This was probably a result of slow canopy closure due to cold conditions, which limited leaf expansion (Fasi et al., 2008). A comparison of the temperature adjusted growth rates of the treatment sites, being the slope of each regression, found no significant differences (0.483<P<0.486). From September 2011 through to April/May 2012, the TAGR was 3.9±0.16 kg DM/ha/*Cd. From April/May 2012 to September 2012, the TAGR was 1.6±0.20 kg DM/ha/*Cd. When assessed on an annual basis, the pasture in the lysimeters, channels and cages all grew at an average temperature adjusted rate of 3.35±0.15 kg DM/ha/*Cd (P=0.291). The fitted regressions in Figure 3.13 have y-axis intercepts ranging from 1309-2507 kg DM/ha, which represents the residual herbage at the start of the experimental period.
Table 3.11  Influence of sampling location (i.e. lysimeters, channels and cages) on temperature adjusted growth rates (TAGR) (kg DM/ha/°Cd) of perennial ryegrass/white clover pastures at Larundel Dairy Farm, Canterbury, for the period 09/09/2011 to 07/09/2012, above a base temperature of 3°C.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>09 Sep 11 – Apr-May 12&lt;sup&gt;1&lt;/sup&gt;</th>
<th>Apr-May 12&lt;sup&gt;2&lt;/sup&gt; – 07 Sep 12</th>
<th>Annual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lysimeters&lt;sup&gt;2&lt;/sup&gt;</td>
<td>3.6</td>
<td>1.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Channels</td>
<td>4.0</td>
<td>1.6</td>
<td>3.4</td>
</tr>
<tr>
<td>Cages</td>
<td>4.1</td>
<td>1.9</td>
<td>3.7</td>
</tr>
<tr>
<td>Site</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>SEM</td>
<td>0.16</td>
<td>0.20</td>
<td>0.15</td>
</tr>
</tbody>
</table>

Note 1: The actual dates when TAGR changed were 15/04/2012, 01/04/2012 and 02/05/2012 for the lysimeters, channels and cages respectively.

Note 2: Missing values were used for L1 in the analyses.

Figure 3.13  Accumulated total herbage yield against accumulated thermal time (Tt) of perennial ryegrass/white clover pastures at Larundel Dairy Farm, Canterbury for the period 09/09/2011-07/09/2012, above a base temperature of 3°C. Treatments are lysimeters (▲), channels (■) and cages (◇). Treatment means for the lysimeters excluded L1 (△). Dates when the temperature adjusted growth rates (slopes of lines) change are indicated. Forms of the fitted lines, up until the changes in the TAGR, are \( y = (3.6±0.11)x + 2254±87.8 \ (r^2=0.99) \) (lysimeters), \( y = (4.0±0.08)x + 1309±75.6 \ (r^2=0.99) \) (channels) and \( y = (4.1±0.16)x + 2507±144.0 \ (r^2=0.99) \) (cages).

3.3.4  Botanical composition

Annually, there were no differences (0.084<p<0.887) in the grass, weed, clover, and dead material components among the lysimeters, channels and cages (Figure 3.14). However, a build-up of dead material occurred at the base of the pasture sward in the lysimeters (Plate 3.5a) and channels (Plate 3.5b). This was unable to be quantified because it was below the cutting/grazing height. The same build-up of dead material was not observed in the cages (Plate 3.5c) and possibly explains the higher
HGR in the cages (P=0.027) for Regrowth 8 (Figure 3.12). On average, grass contributed 78%, weed 15%, dead material 7% and clover <1% of the herbage (Figure 3.14).

The grass, clover, weed and dead material composition of the lysimeters, channels and cages did not differ seasonally (0.092<P<0.889) (Figure 3.15). However, during autumn the cages had a lower proportion of dead material (6±0.6%) compared with the lysimeters and channels (10±0.6%) (P=0.041). During winter the cages had a higher (P=0.018) proportion of grass (93±1.9%) and lower (P=0.009) proportion of weed (3±1.1%) than the lysimeters and channels at 79±1.9% and 13±1.1%, respectively. The winter dead material component in the lysimeters (9±0.7%) exceeded (P=0.041) that in the channels (6±0.7%) and cages (4±0.7%), probably due to cutting of the pasture compared with grazing.

Overall, the grass component was lowest (P<0.001) and the weed component highest (P<0.001) during the summer months, making up 72±1.9% and 23±1.6% of the pasture compared with 83±1.9% and 9±1.6%, respectively, in winter, autumn and spring. There were no differences (P=0.137) in the clover composition between seasons, contributing <1±0.3% throughout the year. The proportion of dead material was greatest (P<0.01) in spring (9±0.8%), followed by autumn and winter (7±1.6%) and summer (4±1.6%). The weed component consisted predominantly of dandelion (*Taraxacum officinale*).

Plate 3.5  Lysimeter L2 pasture at Larundel Dairy Farm, 02/07/2012 (a), channel C2 pasture at Larundel Dairy Farm, 02/07/2012 (b) and caged pasture at Larundel Dairy Farm, 02/07/2012 (c). Tape measure length is 200 mm.
Figure 3.14  Mean annual botanical composition of perennial ryegrass-based pasture in the lysimeters, channels and cages at Larundel Dairy Farm, Canterbury for the period 09/09/2011-07/09/2012. Botanical components identified were grass (■), white clover (□), weed (▩), and dead material (▨). Results are presented as a percentage of the total herbage yield. L1 measurements were excluded from the lysimeters. Error bars show the standard errors of the means.

Figure 3.15  Mean seasonal botanical composition of perennial ryegrass-based pasture in the lysimeters, channels and cages at Larundel Dairy Farm, Canterbury for the period 09/09/2011-07/09/2012. Botanical components identified were grass (■), white clover (□), weed (▩), and dead material (▨). Results are presented as a percentage of the total herbage yield. L1 measurements were excluded from the lysimeters. Error bars show the standard errors of the means.
3.3.5 Pasture height

The height of the pasture in the lysimeters, channels and cages all followed a similar trend (Figure 3.16). Following each grazing event, the pasture height was reduced to a residual of 50-60 mm, which was followed by a steady increase from September to May, reaching a maximum height of 340-440. After the final grazing event of the milking season in early May 2012, the pasture height increased to 100-140 mm by the end of May 2012 and then remained relatively unchanged through winter. A decrease in height of 10-30 mm was observed at all sites from July to August. New growth occurred from August with pasture height increasing to 170-200 mm in the channels and cages and to ~120-130 mm in the lysimeters by September.

Analysis of the measured, undisturbed pasture heights at the end of each regrowth cycle found no differences (0.064<P<0.811) among the lysimeters, channels, and cages, except for Regrowth 8. For this cycle, the caged pasture height was 260±12.7 mm and greater (P=0.027) than the 176±12.7 mm in the channels and lysimeters, which is consistent with the HGR results (Section 3.3.2). Overall, the mean pasture height across all three sampling locations ranged from 165±15.5 mm in winter to 382±18.6 mm in early spring. The mean height of the pasture throughout the experimental period was 134 mm.

![Figure 3.16](image)

Figure 3.16 Measured height of perennial ryegrass/white clover pasture in the lysimeters (▲), channels (■) and cages (♦) at Larundel Dairy Farm, Canterbury, for the period 09/09/2011 to 07/09/2012. Between measurements, pasture height was assumed to increase linearly. Treatment means for the lysimeters excluded L1 (△). The error bar shows the maximum standard error of the mean of pasture height measurements at the end of each regrowth period.

3.3.6 Leaf area index

Increases in PAR interception occurred up to a LAI_\text{cept} of ~4.0. Beyond this point, the canopy intercepted ~95% of the PAR (Figure 3.17). Channel measured LAI_\text{cept} values ranged between 0.19 and 5.11, with associated PAR interception of 15.1% to 98.8%, respectively. The relationship between LAI_\text{cept} and PAR
interception yielded a high $r^2$ of 0.97. The relationship between the GAI of the cut pasture and PAR interception followed a similar, although looser relationship, reflected by an $r^2$ of 0.66 (Figure 3.17). GAI was, as expected, lower than the estimated LAI\textsubscript{cept} values (Section 3.2.5.3), reaching a maximum of 3.3. At a GAI of 1.6, 95% of PAR was intercepted.

There was a strong relationship between channel measured LAI\textsubscript{cept} and GAI with an $r^2$ of 0.85 (Figure 3.18). ANOVA identified no differences between the GAI of the channels and the lysimeters ($0.098 < p < 0.954$) (Figure 3.19). Daily time series of LAI\textsubscript{cept} values estimated for the lysimeters is illustrated in Figure 3.20. LAI was assumed to increase linearly between measurement dates, and reduce to 0.6 after grazing. However, the initial LAI was likely greater than 0.6 due to the larger (~1.5 t DM/ha) herbage residual post grazing/clipping (Section 3.3.2). The initial LAI was therefore estimated at 1.5 based on linear regression (not shown) of clipped lysimeter herbage mass against estimated LAI, assuming a starting residual of 1.5 t DM/ha (i.e. 0.5 t DM/ha above the standard 1.0 t DM/ha residual). As with growth rate and height, an initial peak in November was followed by a number of smaller peaks at the end of each subsequent regrowth cycle.

![Figure 3.17](image-url) Ceptometer measured photosynthetically active radiation (PAR) interception by the canopy against ceptometer measured leaf area index (LAI\textsubscript{cept}) (▲, △) and laboratory measured green area index (GAI) (●, ○) of perennial ryegrass/white clover pasture at Larundel Dairy Farm, Canterbury. Closed symbols represent channel measured values. Open symbols represent measurements taken in the wider pasture during late winter and early spring, both pre- and post- cutting to give a full spectrum of results. Forms of the fitted lines are $y = (1.01\pm0.02) - (1.05\pm0.03) \times (0.42\pm0.02)^x$ ($r^2=0.97$) for the relationship between PAR interception and LAI\textsubscript{cept} (—), and $y = (0.98\pm0.03) - (1.11\pm0.35) \times (0.10\pm0.06)^x$ ($r^2=0.66$) for the relationship between PAR interception and GAI (---).
Figure 3.18  Ceptometer measured leaf area index (LAI\textsubscript{cept}) against green area index (GAI) of perennial ryegrass-based pasture at Larundel Dairy Farm, Canterbury. Form of the fitted line is $y = (6.53 \pm 0.800) - (8.45 \pm 0.740) * (0.44 \pm 0.110)^x$ ($r^2 = 0.85$). Closed symbols represent channel-measured values. Open symbols represent values measured in the wider paddock area during late winter and early spring.

Figure 3.19  Lysimeter (▲) and channel (■) measured green area index (GAI) of perennial ryegrass pasture at Larundel Dairy Farm, Canterbury, for the period 09/09/2011-07/09/2012. Each point represents the GAI at the end of a full regrowth cycle. Treatment means for the lysimeters excluded L1 (▲). The error bar shows the maximum standard error of the mean.
Figure 3.20 Estimated mean daily lysimeter leaf area index (LAI) of perennial ryegrass pasture at Larundel Dairy Farm, Canterbury, for the period 09/09/2011-07/09/2012. LAI was estimated from measured lysimeter green area index data using the calibration equation from Figure 3.18 ($y = 6.53 - 8.45 \times 0.44^*$). The initial LAI was estimated from linear regression of end of regrowth cycle measured (clipped) herbage mass against LAI for the lysimeters, assuming a residual of 1.5 t DM/ha.

3.3.7 Herbage nitrogen

For eight of the nine end of regrowth cycle measurements (Regrowths 1-5 and 7-9), there were no differences (0.065<P<0.694) in the nitrogen concentration (N%) of the pasture in the cages and lysimeters (Figure 3.21a). During each of these regrowth cycles, the N% of the pasture ranged from a minimum of 1.9±0.09% (Regrowth 1) to a maximum of 3.5±0.13% (Regrowth 9). At the end of the regrowth cycle ending 20/02/2012 (Regrowth 6), the N% of the caged pasture (3.8±0.01%) was statistically different (P=0.015) from that of the lysimeters (3.7±0.01%), although in practice this difference is minor. The NNI of the cage and lysimeter pasture yields at the end of each grazing rotation (Figure 3.21b) ranged between 0.47 and 0.83. For all nine regrowth cycles, the NNI of the lysimeters was limiting at <0.8. For the cages the NNI was <0.8 for seven of the nine regrowth cycles.
Figure 3.21 Nitrogen content (N%) (a) and the nitrogen nutrition index (NNI) (b) of harvested perennial ryegrass-based pasture in the lysimeters (▲) and cages (◆) at Larundel Dairy Farm, Canterbury, for the period 09/09/2011 to 07/09/2012. Each point represents the N% at the end of a full regrowth cycle. The error bar shows the maximum standard error of the mean for the end of regrowth cycle pasture N% measurements. The horizontal black line represents the optimum NNI of 1.0 (——), and the dashed black line (—–) represents an NNI of 0.8, below which N is limiting. Treatment means for the lysimeters exclude L1 (△).

3.3.8 Calibration of DairyMod at Larundel Dairy Farm

Simulated total herbage yield for the lysimeter-grown pasture was 11.3 t DM/ha, 6% more than that measured in the lysimeters (Figure 3.22). Over the experiment, differences at the end of each regrowth cycle between the observed and simulated ranged from 0.01-0.90 t DM/ha (1-130%). Statistical comparison of the observed and simulated herbage yields on a regrowth cycle gave an NSE of 0.85 and NRMSD of 0.31. A lack of uniformity accounted for 98% of the MSD, indicative of a well distributed bias and a slope close to one and intercept close to zero Figure 3.23.

Figure 3.22 Observed mean lysimeter (▲), cage (◆) and channel (■) and DairyMod-simulated (——) accumulated herbage yield above the residual grazing height of perennial ryegrass/white clover pasture at Larundel Dairy Farm, West Eyreton, Canterbury for the period 09/09/2011-07/09/2012.
Figure 3.23  Residual analysis of observed and DairyMod-simulated herbage mass above the residual grazing height, of perennial ryegrass/white clover pasture at Larundel Dairy Farm, Canterbury for the period 09/09/2011-07/09/2012. (a) shows the relationship between the observed and simulated yields for each regrowth cycle where solid lines (—) show the 1:1 relationship and dotted lines (---) are the fitted lines, (b) shows the residual yields (simulated-observed) over time and (c) the segmentation of the MSD in to the squared bias (□) and the lack of correlation (■). Form of the fitted line in (a) is \( y = (1.02 \pm 0.16)x - 0.10 \pm 0.24 \) \((r^2=0.85)\)

Simulated pasture leaf area index and height are compared with the lysimeter-grown pasture LAI and height measurements in Figure 3.24. Simulated LAI varied between 0.6 and 6.2 compared with the lysimeter data, which varied between 0.6 and 5.8. On average, the simulated mean daily LAI (1.8) was 0.3 less than the mean daily observed LAI (2.1). Simulated canopy height varied between 43 and 346 mm compared with 60 and 365 mm by the observed. The simulated mean daily canopy height (115 mm) was 15 mm less than the measured (130 mm) value. The NSE coefficients and NRMSD values were 0.52 and 0.58 for LAI and 0.60 and 0.30 for pasture height, respectively. Residual analysis identified a systematic under-estimation of both LAI and height, reflected by an SB contribution of 12% and 43% to the calculated MSDs, respectively. The potential effects of the assessed biases on PET estimations are discussed in Section 3.4.2 and quantified in Chapter 4.
3.3.9 DairyMod-simulated herbage yields at Three Springs Dairies and Pendo Farms

Simulated total accumulated herbage yields for the lysimeter-grown ryegrass/white clover pastures at TSD and PF were 12 t DM/ha and 14.9 t DM/ha for the period 09/09/2011 to 07/09/2012 (Figure 3.25), 13% and 41% more than that measured in the lysimeters at LDF (10.6 t DM/ha), respectively (Table 3.12). At TSD, the simulated yield compared with that observed on farm (Nigel Gardner, pers. comm., Sept. 2014). Paddock herbage yields ranged from 1.0 t DM/ha at both TSD and PF following grazing up to 2.4 t DM/ha (TSD) and 3.2 t DM/ha (PF) at the end of each regrowth cycle.

The daily simulated pasture LAI and height values follow the grazing patterns at TSD and PF (Figure 3.26), peaking at the end of each simulated regrowth cycle and reducing to residual LAI values of 0.7 and residual pasture heights of 47-50 mm. Both LAI and height were maximal at the end of the
experimental period following winter growth at PF. On average, the height and LAI of the pasture at PF exceeded that at TSD by 8 mm and 0.1, respectively. When compared with that measured at LDF, LDF had a higher mean LAI (2.1) and pasture height (130 mm) (Table 3.12).

Figure 3.25  Simulated total daily herbage mass (left) and accumulated daily herbage yields (right) of perennial ryegrass/white clover pastures at Three Springs Dairies (—) and Pendo Farms (—), for the period 09/09/2011-07/09/2012.

Figure 3.26  Simulated daily pasture leaf area index (LAI) (left) and pasture height (right) of perennial ryegrass/white clover pastures at Three Springs Dairies (—) and Pendo Farms (—), for the period 09/09/2011-07/09/2012.
Table 3.12  Summary of herbage yields, pasture leaf area index and pasture height at Larundel Dairy Farm (LDF), Three Springs Dairies (TSD) and Pendo Farms (PF) for the period 09/09/2011-07/09/2011. Values for LDF are the measured values except for the mean daily herbage yield at LDF, which was based on the daily simulated data.

<table>
<thead>
<tr>
<th>Canopy variable</th>
<th>Statistic</th>
<th>LDF</th>
<th>TSD</th>
<th>PF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total accumulated herbage yield (t DM/ha)</td>
<td></td>
<td>10.6</td>
<td>12.0</td>
<td>14.9</td>
</tr>
<tr>
<td>Number of regrowth cycles</td>
<td></td>
<td>9</td>
<td>11</td>
<td>16</td>
</tr>
<tr>
<td>Paddock herbage yields (t DM/ha/d)</td>
<td>Mean</td>
<td>1.6</td>
<td>1.4</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>3.2</td>
<td>2.4</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Leaf area index</td>
<td>Mean</td>
<td>2.1</td>
<td>1.5</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
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<td>2.9</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>0.6</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Canopy height (mm)</td>
<td>Mean</td>
<td>130</td>
<td>100</td>
<td>108</td>
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<tr>
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<td>Maximum</td>
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<td>185</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td>Minimum</td>
<td>60</td>
<td>47</td>
<td>50</td>
</tr>
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</table>
3.4 Discussion

This chapter described and quantified growth of irrigated, grazed perennial ryegrass/white clover swards grown under commercial Canterbury dairy farming operations, and calibrated the pasture growth model DairyMod using the observed canopy data, thereby achieving Objectives 2 and 3 of this research. These steps were essential in the process of testing the research hypothesis to enable understanding of the canopy development in the interpretation of evapotranspiration once quantified in Chapter 4.

3.4.1 Agronomic performance of perennial ryegrass/white clover pasture at Larundel Dairy Farm

The ryegrass-based pasture grown in the lysimeters at LDF was representative of that grown in the wider paddock area. While optimal herbage yields were not achieved (Section 2.3.2.1), when the measured and simulated pastures at LDF, TSD and PF are compared with that reported in the literature for Canterbury, growth was typical of nitrogen-deficient pasture in the region.

3.4.1.1 Herbage dry matter production

At LDF there were no differences (P=0.153) in the total accumulated pasture yield from the lysimeters, channels, and cages, from which 10.8±0.88 t DM/ha was produced from 09/09/2011-07/09/2012 (Figure 3.11). Mean annual ryegrass yields in Canterbury have been reported to range between approximately 10 t DM/ha/y to more than 20 t DM/ha/y (Black & Murdoch, 2013; Easton et al., 2001; Horne et al., 2011) (Section 2.3.2.1). While the measured yield at LDF was within the range reported in other studies for Canterbury, it was at the lower end. Despite the estimated actual soil moisture deficits, suggesting water was likely to be limiting to the canopy (Section 3.2.4.3), in practice, water was not expected to have limited growth based on actual soil moisture measurements (Section 4.3.1.2). This was supported by the linear relationship between herbage accumulation and thermal time (Figure 3.13). If water had been limiting, the relationship would not have been linear throughout the growing season (Tonmukayakul, 2009). Temperature was also found to be not limiting to growth (Figures 3.4 and 3.13). Therefore, the nitrogen status of the pasture was investigated (Section 3.4.1.7).

3.4.1.2 Herbage growth rates

Mean daily HGR of the pasture in the lysimeters, channels and cages over each regrowth cycle ranged between 6.5-69.0 kg DM/ha/d (Figure 3.12). These compared with average seasonal values reported by Rickard and Radcliffe (1976) and McBride (1994) for ryegrass-based pastures at Winchmore, Canterbury (3-56 kg DM/ha/d), and growth rates published by Baars et al. (1991) for North Island grown ryegrass pastures (5-90 kg DM/ha/d) (Section 2.3.2.1). These studies also showed rapid increases in growth during early spring due to increased temperatures, similar to that observed at LDF. Lynch (1949), for example, found ryegrass pasture growth in Canterbury to be dominant during spring,
followed by a summer slump in response to a change from the vegetative to the reproductive phase (Radcliffe & Baars, 1987), as also occurred at LDF. Similarly, Brougham (1959) reported rapid increases in early spring followed by a more gradual decline in summer in response to higher temperatures.

There were no differences (0.085<P<0.84) in the growth of the pasture among the three measurement areas throughout the study, except for during autumn when the growth in the cages was greater (P=0.027) than in the channels and lysimeters. At this time there was a build-up of dead material at the base of the pasture sward in the channels and lysimeters (Plates 3.5a and 3.5b), which was not observed in the cages, as illustrated by Plate 3.5c. This probably restricted pasture growth in the channels and lysimeters compared with that of the cages. However, in practice such a difference would be considered minor.

3.4.1.3 Temperature adjusted pasture growth

Thermal time was quantified to compare pasture growth between the cages, lysimeters and channels, without the influence of temperature variance.

The TAGR of the pastures at LDF of 3.9±0.16 kg DM/ha/°Cd from September 2011 to May 2012 (Figure 3.13) was similar to the 4.1 kg DM/ha/°Cd reported by Tonmukayakul (2009) for a nitrogen-limited ryegrass/white clover pasture. Table 5.11 in Chapter 5 also identifies low annual TAGR values for irrigated, ryegrass-based pastures without N fertilisation of 4.3-5.2 kg DM/ha/°Cd. With N fertiliser, however, rates increased to 7.5 kg DM/ha/°Cd. Mills (2007) found rates of 7.2 kg DM/ha/°Cd were possible for a cocksfoot pasture, where neither water nor nitrogen were limiting (Section 2.3.2.3). The linear nature of the relationship between accumulated yield and thermal time in Figure 3.13 indicates that neither water nor temperature were limiting to growth. These results therefore suggest nitrogen was limiting to growth at LDF, which has been discussed further in Section 3.4.1.7.

The flattening out of the relationship between accumulated herbage mass and accumulated Tt during April/May 2012 suggested that leaf extension was slow to recover after the last grazing of the season in early May (Figure 3.13), which resulted in a longer lag phase until the next season’s growth commenced with increased spring temperatures.

The observed herbage mass accumulation has been compared to the potential non-limited herbage mass accumulation with a TAGR of 7 kg DM/ha/°Cd in Table 3.13. This enabled the potential production losses in the lysimeters at LDF due to insufficient N, as reflected in the low NNI values of 0.47-0.74 (Figure 3.21), to be quantified. The comparison was undertaken for Regrowths 1-8, being the period (approximately) up to the point at which the TAGR changed (Figure 3.13). The method used by Lemaire et al. (1989) was applied to estimate non-limited herbage nitrogen (i.e. a NNI of least 0.8) as both a percentage of herbage mass and as a kg N/ha equivalent. This was compared with the measured nitrogen content of the herbage at LDF (Section 3.3.7). Herbage mass accumulation at LDF was
estimated to be ~64% of the optimum (Table 3.13). To attain optimum production with an NNI of 0.8, the pasture required 213 kg N/ha more nitrogen in addition to the 207 kg N/ha actually applied, totalling ~420 kg N/ha. Nitrogen deficiency therefore limited pasture growth.

Table 3.13 Comparison of actual herbage mass (HM) and herbage nitrogen (N) content at Larundel Dairy Farm compared with that under non-limiting nitrogen conditions for Regrowths 1-8 (09/09/2011- 04/05/2012).

<table>
<thead>
<tr>
<th>Regrowth cycle</th>
<th>Thermal time (Tt)</th>
<th>Optimum HM (kg DM/ha)</th>
<th>Actual HM (kg DM/ha)</th>
<th>Optimum herbage N</th>
<th>Actual herbage N</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>N% kg N/ha DM</td>
<td>N% kg N/ha DM</td>
</tr>
<tr>
<td>1</td>
<td>383</td>
<td>2682</td>
<td>3809</td>
<td>2.8</td>
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<tr>
<td>2</td>
<td>208</td>
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<tr>
<td>3</td>
<td>259</td>
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<tr>
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<td>2443</td>
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<td>15652</td>
<td>10032</td>
<td>3.1</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Note 1: Optimum HM calculated based on growth rate of 7.0 kg DM/ha/°Cd.
Note 2: Actual HM is the observed lysimeter herbage mass for each regrowth cycle.
Note 3: Optimum herbage N based on achieving a nitrogen nutrition index = 0.8.

However, despite the low NNI values at LDF, the actual herbage N, excluding the first regrowth cycle, averaged ~3%, and only differed by 0.1-0.5 from the optimums estimated (Table 3.13). According to Peri (2002), at a nitrogen content of 3%, photosynthesis should be at ~80% of the maximum (Figure 2.3). However, even if an additional 20% herbage production is added to the measured lysimeter herbage yield, which would give 12 t DM/ha, the optimal yield of 16 t DM/ha from September to May is still not attained. As neither water nor temperature were limiting and the leaf nitrogen content was not critical to photosynthesis, the reduced herbage production was likely in response to a loss of leaf area. This is not surprising as one of the principal effects of nitrogen supply on growth is in relation to canopy expansion and therefore light interception (Section 2.3.2.4). In the current study, it appears the pasture responded to the sub-optimal nitrogen supply through maintenance of a nitrogen content of ~3%, achieved through a reduction in the leaf area, which subsequently led to the observed sub-optimal herbage production. With higher N inputs, the pasture would have maintained a similar leaf nitrogen content, as indicated in Table 3.13. However, higher production would have resulted in response to greater leaf expansion and light interception. This compares with that reported by Grindlay (1997) for field crops (e.g. wheat, *Triticum* spp.) and Fergusson (1999) for Barley (*Hordeum vulgare* L.), whereby the green area of the lamina was adjusted to control the nitrogen content in order to match the photosynthetic flux density during growth and maximise use of intercepted radiation.
Accordingly, sole reliance on the nitrogen content of the pasture as a percentage of dry matter to quantify the N nutrition may not be sufficient.

### 3.4.1.4 Botanical composition

The seasonal trend of a reduced grass component in summer followed by an increase and peak during autumn (Figure 3.15) mirrored the trend identified by Baars et al. (1991) for a ryegrass/white clover pasture. Baars et al. (1991) also found the weed content of the sward increased in summer. The clover component, however, was greater than that measured at LDF, where clover growth was probably suppressed by clover root weevil (Sitona lepidus) (B. McKercher, pers. comm., 4 Dec. 2012).

The extended rotation period during spring when the pasture was grazed in early September and then spelled for seven weeks prior to harvesting for silage probably led to the senescence of older leaves as newer leaves were initiated. This increased the dead material component during the spring (Figure 3.15). Fulkerson and Donaghy (2001) found that grazing or defoliation at the ‘3-leaf’ stage reduces senescence and stem build up and therefore produces higher quality herbage. Pasture growth beyond this stage increases senescence. Following the silage harvest, regular grazing throughout summer led to higher utilisation of the pasture, allowing the development and growth of new shoots and a reduction in the dead material component.

The build-up of dead material at the base of the pasture sward in the lysimeters and channels was reflected by the greater (P=0.041) proportion of dead material measured during autumn. At the end of the grazing season in May 2011, the cages were removed and on-going sampling of the wider paddock to quantify winter growth occurred outside of the original cage boundaries. For the lysimeters and channels, however, all measurements and sampling continued in-situ. Unlike in the lysimeters and channels where the pasture had been cut with grass shearers, cattle had defoliated the pasture in the wider paddock during the previous milking season where the winter measurements were taken. Defoliation by grazing involves ripping of the pasture (Porter, 2008) and therefore has a different effect compared with manual cutting (Cayley & Bird, 1991). This probably led to the differences in the weed (P=0.009) and grass (P=0.018) components observed among the treatments in winter. Annually however, no significant differences (P=0.09-0.712) existed in the botanical composition of the pasture produced in the lysimeters, channels and cages, and therefore the pasture data from the lysimeters was considered representative of the wider paddock.

### 3.4.1.5 Pasture height

As with growth rates, pasture height peaked in early spring, reaching 382±18.6 mm in the lysimeters, channels, and cages (P=0.064) (Figure 3.16). Regular (approximately three weekly) clipping/grazing by stock throughout the remainder of the growing season (i.e. until May) kept pasture height below ~250 mm. Differences in the measured pasture height at the end of Regrowth 8, where the lysimeters and
channels were 32% shorter (P=0.027) than the cages, was probably due to the restricted growth in the channels and lysimeters caused by the build-up of dead material at the base of the pasture sward (Section 3.3.4).

3.4.1.6 Leaf area and light interception

Use of the relationship established between LAI\textsubscript{cept} and GAI of the channels (Figures 3.18 and 3.19) was found to be appropriate for estimating lysimeter LAI. Estimated LAI values of the lysimeter pasture ranged between 0.6, being the residual LAI after grazing, to a maximum of 5.8 following a seven-week period of growth during September-November 2011 (Figure 3.20). At the end of the first season grazing, however, the LAI of the residual herbage was estimated to be 1.5 (Section 3.3.6). According to Korte \textit{et al.} (1982), post-grazing residual LAI values of 0.1-0.9 occur under a hard-grazed system, whereas residual LAI values of 0.9-3.0 could be expected under lax grazing (Section 2.3.2.5). The initial LAI of 1.5 was therefore representative of a more lax grazing event and the 0.6 representative of residual herbage under a hard-grazed system.

At LDF, 95% interception in the channels was achieved at a LAI\textsubscript{cept} of approximately four (Figure 3.17), which is slightly higher than the value of three given by Akmal and Janssens (2004). The difference, however, may be attributable to the difference in measurement. In the current study measurements were taken at ground level through the use of channels, while it appears LAI values reported by Akmal and Janssens (2004) may have involved the instrumentation sitting on the soil surface. However, both values are within the range of 2.3-5 reported in the literature for ryegrass-based pastures by Brougham (1958) and Bircham and Hodgson (1983) (Section 2.3.2.4). In the current experiment, an LAI of at least four was achieved only 12% of the time, suggesting that for 88% of the experiment, pasture growth was below the maximum potential. This supports the assertion that the pasture was controlling canopy expansion in order to maintain a leaf nitrogen content of ~3% to optimise the use of the radiation captured (Grindlay, 1997), as discussed in Sections 3.4.1.3 and 3.4.1.7.

3.4.1.7 Nitrogen

Nitrogen concentrations of the pasture were lowest at the end of Regrowth 1 (01/11/2011), averaging 1.95% (Figure 3.21). A nitrogen concentration of 2.6% is the critical value below which photosynthesis is severely constrained, while a concentration of 5.2% or greater is considered maximal (Peri \textit{et al.}, 2002b) (Section 2.3.2.4). At the measured concentration of 1.95%, photosynthesis was only about 65% of the potential rate (Figure 2.3). However, the low value is likely a reflection of the inclusion of reproductive seed heads in the pasture sample, which contain more structural material with a lower nitrogen content (Section 2.3.2.1). Furthermore, the seven week period of non-grazing for the silage harvest resulted in a higher proportion of senesced material (Section 3.3.4), which also has a lower nitrogen status (Wilman \textit{et al.}, 1976). The nitrogen ratio of the leaf and stem (including inflorescence)
fractions were not determined in this study. However, a third of the total nitrogen has been associated with the stem fraction for a cocksfoot pasture by Waghorn et al. (1989). The leaf:stem fractions of ryegrass during flowering average 25:75, where the stem fraction includes the leaf sheath, stem, inflorescence and dead material (Chaves et al., 2006; Terry & Tilley, 1964). Using this ratio and the nitrogen ratio given by Wilman et al. (1976), the leaf nitrogen concentration of the perennial ryegrass pasture at the end of the first grazing rotation at LDF could be estimated to be about 2.3%. While this is greater than 1.95%, it is still nitrogen-limited. The absence of white clover (Section 3.3.4) reducing the fixation potential and the limited nitrogen fertiliser application pre-November, which consisted of a single 50 kg/ha application of urea in early September (Section 3.2.4.4), were both likely contributors to the low herbage N status.

During summer, increased mineralisation of applied nitrogen with warmer temperatures (McLaren & Cameron, 1996) resulted in the nitrogen concentration of the pasture being maintained at ~3.2%, on average, at which ~80% photosynthesis is expected (Peri, 2002; Peri et al., 2002b). This indicates the leaf nitrogen content was not critically limiting to photosynthesis. Maximum values of 3.8±0.002% and 3.7±0.002% were achieved in the cages and lysimeters, respectively, at the end of February 2012, which was followed by a decline into autumn as temperatures cooled and mineralisation decreased. Increases in the herbage N content the following spring were probably attributable to increased mineralisation with increasing temperatures (Figure 3.4).

While, for a majority of the experiment, the leaf nitrogen was sufficient to maintain at least 80% photosynthetic efficiency (Figure 2.3), the nitrogen status, when assessed using the NNI, highlighted limiting nitrogen conditions in the lysimeter-grown pasture throughout the entire study period (Figure 3.21). Mills et al. (2009) identified nitrogen deficiency to be the primary limiting factor in cocksfoot pasture production and found the accumulated herbage yield of irrigated cocksfoot pasture with an NNI of ~0.3-0.7 was less than half that of an irrigated cocksfoot pasture with an NNI above 0.8. Grindlay (1997) identified that the growth of leaves, and therefore herbage production, is a principal determinant of nitrogen demand as large contents of reduced nitrogen are required for photosynthetic leaf function. However, as discussed in Section 2.3.2.4, the influence of nitrogen supply on herbage production is not direct; rather the effect is on canopy expansion, and therefore the amount of radiation intercepted by the canopy. The canopy will control leaf extension in relation to the nitrogen available to maintain a specific leaf nitrogen in order to optimise photosynthetic efficiency (Grindlay, 1997). This was reflected at LDF where the pasture maintained a nitrogen content of ~3%. The fluctuations in the data around this value were due to fluctuations in the pseudostem nitrogen content, rather than the leaf. This is supported by Mills (2007) who identified that fluctuations in the N content of a cocksfoot pasture were not evident in the nitrogen of the leaf component of the pasture when it was separated from the pseudostem, although the pseudostem maintained the fluctuations. For
example, on 01/09/2005 and 17/10/2005 Mills (2007) reported the N content of the pasture ranged from 2-3.8% and 2.8-5%, respectively, under treatments of irrigation and nitrogen. However, despite the varying levels of N on each date, the specific leaf nitrogen was maintained at ~1.0 g N/m² lamina (01/09/2005) and ~1.6 g N/m² lamina (17/10/2005). Meanwhile, the specific pseudostem nitrogen varied from ~1.3 g N/m² lamina, on both dates, with nitrogen content.

In response to the sub-optimal herbage accumulation at LDF caused by limited nitrogen supply (Table 3.13), DairyMod was used to model the effects on leaf extension and therefore herbage production if the estimated total nitrogen (420 kg N/ha) required to achieve optimal production (Section 3.4.1.3) was applied. The results of the simulation showed only a 4% (416 kg DM/ha) increase in the total yield, in response to a 0.01 (<1%) increase in the leaf area index and 0.1 kg C/ha/d (1%) increase in net photosynthesis. When the temperature stress values published by White et al. (2008) were used (Table 2.1) instead of those determined in the model calibration (Table 3.8), DairyMod estimated the accumulated herbage yield at LDF to be 14.8 t DM/ha/y. This equated to an over-estimation of 3.2 t DM/ha/y (39%), and the NSE fell to 0.52. However, if the nitrogen applied was increased to the 420 kg N/ha/y, the simulated herbage yield, with the White et al. (2008) temperature values, totalled 18.7 t DM/ha, an increase of 3.9 t DM/ha/y. This was in response to an increase of 5% in LAI and 8% in net photosynthesis from the increased nitrogen fertiliser. Accordingly, at the high temperature stress values determined in the sensitivity analysis at LDF (Table 3.8), temperature was more limiting than nitrogen availability, and therefore wouldn’t allow a nitrogen response. However, while the modelled results suggest that the pasture at LDF was limited by temperature, not nitrogen, this contrasts with the observed data, whereby temperature was not found to be limiting (Figure 3.13). Therefore, while DairyMod is capable of triggering a nitrogen response, the temperature parameter values required to achieve this at LDF are unsuitable.

### 3.4.2 Use of DairyMod for the simulation of pasture growth at Larundel Dairy Farm

The results from the DairyMod simulation show that the model can be used to realistically predict herbage yields of lysimeter-grown ryegrass pasture under a commercial dairy operation in Canterbury (Section 3.3.8). Over the experimental period, the mean daily bias was 1.9 kg DM/h/d, within the range reported by Cullen et al. (2008) of -3.7-6.3 kg DM/h/d. The difference of 6% between the total measured and simulated lysimeter herbage yield over the experimental period was comparable to the accuracy achieved by White et al. (2008) of 2.5% for irrigated, fertilised ryegrass pasture, and at the lower end of the differences (0.4-30.3%) published by Cullen et al. (2008). The NSE coefficient and NRMSD achieved (Section 3.3.8) indicate close agreement and provide further confidence in the use of the model to simulate herbage growth. The high LC component (96%) of the MSD indicates the deviation of the simulated yields to be largely random, which is relatively less easy to be ‘fixed’
compared with if the errors were more systematic, which would be represented by larger SB and/or NU components (Gauch et al., 2003) (Section 2.5).

Accurate estimates of plant height and LAI are important for the estimation of PET, in Chapter 4, and underlie the reason for modelling pasture growth in this research. The simulated mean daily LAI and height under-estimated the observed by an average of 0.3 and 15 mm (Section 3.3.8), respectively. At LAI values above the critical 4.0 (Figure 3.17), maximum transpiration and photosynthesis occurs as most of the available radiation is intercepted by the canopy (Brougham, 1958; Pearce et al., 1965). Therefore, where both the simulated and observed values exceed 4.0, the effect of the assessed bias is minor. However, below the critical LAI, the bias can lead to an under-estimation of transpiration, and potentially evapotranspiration, as less radiation will be intercepted by the canopy. Chapter 5 will therefore assess the effects on PET by comparing estimations using observed and simulated canopy LAI and height data for the lysimeters.

The pasture parameter values used in the modelling (Table 3.8) have been compared to those identified by White et al. (2008) as being representative of a perennial ryegrass pasture in Canterbury (Section 2.3.2.6). In the current study, a rooting depth of 400 mm was found to provide the best fit to the observed data, the same as that applied by White et al. (2008). As at LDF, White et al. (2008) also found that implementing high and low temperature stresses improved model predictions. However, the recovery (130°C sum) low temperature stress value at LDF was greater than the 30°C reported by White et al. (2008). The initial (-1°C) and full (-5°C) temperature stress values at LDF suggested low temperatures had a lesser effect on lysimeter pasture growth compared with the field-grown ryegrass simulated by White et al. (2008), who applied initial and full temperatures of 1°C and -3°C, respectively. Conversely, the initial high (24°C) and full (25°C) temperature stress values applied at LDF were lower than that used by White et al. (2008) (26°C and 30°C), but were necessary to obtain a reasonable fit between the observed and simulated data at LDF. However, as discussed in Section 3.2.6.1, high temperature stress should not be full at 25°C, but should be in the range of 29-31°C (Peri et al., 2002b; White et al., 2008). As highlighted in Section 3.4.1.7, it appears that with the high temperature stress values applied at LDF, temperature becomes a more limiting factor in the model than nitrogen availability, and therefore the temperature response within the model won’t allow a nitrogen response.

The higher NSE coefficient and lower NRMSD achieved without clover (Table 3.8) was in agreement with the measured botanical composition data which found clover to compose <1% of the pasture annually (Figure 3.14).
3.4.3 Use of DairyMod for the simulation of pasture growth at Three Springs Dairies and Pendo Farms

The simulated total accumulated pasture yields for the lysimeters at TSD (12.0 t DM/ha/y) and PF (14.9 t DM/ha/y) were higher to the 10.6 t DM/ha measured at LDF. As at LDF, the herbage yields were low compared with the benchmark perennial ryegrass yield for Canterbury of 21 t DM/ha/y (Black & Murdoch, 2013), but were comparable to yields reported for unfertilised ryegrass-based pastures in the literature. Under dryland, Fasi et al. (2008) found the production of unfertilised pastures to be approximately three times less than fertilised pasture. Similarly, but with irrigation, Hunt and Mortimer (1981) reported annual ryegrass herbage yields of 19.2-29.7 t DM/ha/y with high (up to 2150 kg N/ha/y) nitrogen inputs compared with 11-12.8 t DM/ha/y with low (130 kg N/ha/y) nitrogen inputs. Black and Murdoch (2013) reported annual herbage yields for irrigated perennial ryegrass pastures in Canterbury of 11 and 14 t DM/ha with no nitrogen fertiliser applied compared with 15 and 21 t DM/ha when 400 kg N/ha/y were applied. Despite the predicted soil moisture deficits in Figure 3.2, irrigation of the lysimeters at TSD and PF was sufficient to largely maintain the soil moisture above the critical level, based on actual soil moisture measurements given in Section 4.3.1.2. Therefore, nitrogen not water was the limiting factor. This was confirmed by the estimated daily NNI of the pastures from the modelled nitrogen content (Figure 3.27), which indicated the pastures were nitrogen-limited (NNI<0.8) 26% of the time at TSD and 29% of the time at PF.

These results, combined with those for LDF, suggest that nitrogen deficiency is common across dairy farms in Canterbury. However, while annual yields of ≥20 t DM/ha/y have been reported, they typically occur under conditions of luxurious nitrogen fertilisation. Black and Murdoch (2013), for example, achieved yields of up to 21 t DM/ha/y with 400 kg N/ha/year while the 19.2-29.7 t DM/ha yields reported by Hunt and Mortimer (1981) were achieved with extreme annual average nitrogen application rates of 2150 kg N/ha. These equate to 2-10 times the average annual nitrogen applied at LDF, TSD and PF. At LDF, for example, it was estimated that ~100% more N/ha was required (Table 3.13) in addition to the 207 kg N/ha applied, totalling 420 kg N/ha, similar to that applied by Black and Murdoch (2013). However, while greater yields can be achieved, with higher rates of nitrogen come potentially higher economic and environmental costs (McKenzie et al., 1999) which should be considered in parallel with production goals. This is discussed further in Chapter 7.
Figure 3.27  Nitrogen nutrition index (NNI) estimated from the simulated nitrogen content for perennial ryegrass-based pastures at Three Springs Dairies (—) and Pendo Farms (—) for the period 09/9/2011-07/09/2012. The dashed horizontal black line (---) represents an NNI of 0.8, below which N is limiting.

The shorter mean and maximum pasture heights modelled at TSD and PF compared with those measured at LDF (Table 3.12) were due to a combination of the seven-week period of growth during September-November 2011 (Section 3.3.8). Excluding this period, the pasture height at LDF peaked at 220 mm in the lysimeters (Figure 3.24), in between the 185 and 260 mm peak heights at TSD and PF, respectively. As with pasture height, the mean simulated LAI at TSD and PF was 29% and 24% lower than that measured at LDF, respectively. At TSD and PF, the LAI reached a maximum of 2.90 and 4.20, respectively. The maximum LAI achieved at TSD was therefore below the critical value of 4 identified at LDF but within the 2.30-4.70 range typical under grazing (Bircham & Hodgson, 1983). As at LDF, the low LAI of the pastures throughout the experiment was a direct consequence of limiting nitrogen conditions. The minimum LAI values of 0.60 at LDF and 0.70 at TSD and PF were all characteristic of hard-grazed systems (Korte et al., 1982).
3.5 Conclusions

To test the hypothesis of this research, a sound understanding of the canopy and its development over time was required. To achieve this, pasture growth across three sites was quantified through on-site measurements and computer-based simulations using the biophysical model DairyMod. Several conclusions can be drawn from the pasture data.

The data collected at LDF enabled the growth of the lysimeter-grown perennial ryegrass pasture to be described and quantified, as required by Objective 2 (Section 1.4). Specifically, growth in the lysimeters was found to be representative of that grown in the wider paddock area, and of that typical for a nitrogen-deficient pasture within Canterbury.

Differences in pasture growth among the lysimeters (L2 and L3), channels, and cages at LDF was, for eight out of nine rotations, found to be non-significant, based on measurements and analyses of yields, average daily and temperature adjusted growth rates, canopy height, LAI, and canopy botanical composition. However, measurements undertaken at the end of the final regrowth cycle (Regrowth 8) of the 2011/12 season (04/05/2012) identified the cages to be different (P<0.05) to the channels and lysimeters. The pasture in the cages had a higher growth rate, height, LAI, and a greater grass component. On an annual basis, however, no differences were observed among the treatments and it can be concluded that growth in the lysimeters was representative of that in the channels and the wider paddock. Pasture growth in L1 was found to be not representative of the paddock, largely due to its greater flat weed content.

Herbage accumulation at LDF was limited due to nitrogen deficiency, and therefore growth rates and yields were below optimum values identified for a Canterbury ryegrass pasture, but within the range reported in the literature for a nitrogen-deficient pasture in Canterbury. For the period September 2011–May 2012 an additional 5,620 kg DM/ha (56%) could have been produced if nitrogen had been non-limiting. However, inorganic nitrogen applications would have had to have more than doubled to achieve this. The effect on herbage accumulation from the limited nitrogen supply was, however, found not to be direct. Rather, to maximise use of radiation intercepted by the canopy, the pasture leaf area was reduced so that a leaf nitrogen content of ~3% could be maintained.

To achieve Objective 3, the biophysical model DairyMod was calibrated against measured pasture growth data at LDF then used to simulate pasture growth at TSD and PF. Over the experimental period, DairyMod predicted the total herbage accumulation at LDF to be within 6% (0.7 t DM/ha) of that measured. However, the daily LAI and pasture height predictions did not provide as close a match to the observed. Overall, DairyMod under-predicted the mean daily LAI by 0.3 (14%) and mean daily pasture height by 15 mm (11%). From the model, nitrogen limiting conditions were identified to persist
throughout the experiment at TSD and PF. The result was low leaf areas and consequently low total simulated herbage yields of 12 and 14.9 t DM/ha, respectively.

When DairyMod was used to simulate optimal herbage production with increased nitrogen supply at LDF, it was discovered that the temperature parameter values within the calibrated model that were necessary to achieve a reasonable fit with the observed data limited a nitrogen response. Accordingly, despite the nitrogen fertiliser applied doubling, herbage production increased by a mere 0.4 t DM/ha/y and the mean daily leaf area index by 0.01. When temperature values published by White et al. (2008) were used, a nitrogen response was able to be generated. However, the model failed to correctly simulate the observed yield.

Chapter 4 presents the results and a discussion of the pasture water use measurements. Daily outputs of LAI and height for the pastures at LDF, TSD and PF were used in the estimation of $\text{PET}_c$, and the effect of the under-predictions of LAI and pasture height on the $\text{PET}_c$ estimations at LDF examined.
Chapter 4

Quantifying Actual Evapotranspiration from Lysimeter-grown Perennial Ryegrass-Based Pastures, and Evaluation of Potential Evapotranspiration Estimation Methods

4.1 Introduction

This chapter has a focus of quantifying evapotranspiration from three commercial dairy farms across Canterbury, and evaluating a range of standard methods used in its estimation. This addresses the hypothesis that by quantifying evapotranspiration, the degree to which it varies spatially can be quantified, and tests whether improvements can be made to its estimation when models that actively account for variations in the canopy over time are used over those that do not.

Chapter 3 provided a description of pasture growth at Larundel Dairy Farm and enabled the calibration of DairyMod to simulate pasture growth at Three Springs Dairies and Pendo Farms, thereby addressing Objectives 2 and 3 (Section 1.4). Measured and simulated canopy LAI and height data from Chapter 3 were used in this chapter in the estimation of PETc.

Actual evapotranspiration from the lysimeter-grown pastures is quantified for LDF, TSD and PF over the experimental period using measured climate data, irrigation and rainfall inputs, drainage and changes in the soil moisture content (Objective 4). While drainage from the soil was measured by the lysimeters, in many cases lysimeters are impractical to install (Section 2.2.2.1). In such cases, drainage predictions are required to achieve accurate estimations of actual evapotranspiration. Quantifying water flow through the soil profile is also crucial to improving on-farm irrigation efficiency and the management of a limited resource, which is addressed in Chapter 6. The ability of the DairyMod and HYDRUS-1D models to accurately simulate soil water flow is therefore investigated in this chapter (Objective 5).

Crop coefficient time series for each lysimeter site are developed in this chapter and measured and simulated daily pasture LAI and height values for the three farms from Chapter 3 are used to assess standard evapotranspiration models (Objective 6). Specifically, the models’ ability to estimate actual evapotranspiration from irrigated, grazed pastures was evaluated.
4.2  Methods and Materials

Site descriptions for Larundel Dairy Farm, Three Springs Dairies and Pendo Farms were presented in Sections 3.2.1 to 3.2.3. The following sections provide a description of the experimental design, measurements and models used to quantify and predict evapotranspiration from, and soil water flow through, the lysimeters.

4.2.1  Experimental design

4.2.1.1  Lysimeters

Nine drainage lysimeters were installed by Aqualinc Research Limited, three at each of LDF, TSD and PF during 2010 and 2011, as part of the Waterscape Programme (Section 1.4).

Lysimeter installation followed the method outlined in Cameron et al. (1992) (Section 2.2.2.1). Each lysimeter was installed within the field at ground level as an undisturbed, hand cut soil core (Plate 4.1). The lysimeters were each enclosed in a cylindrical steel casing, 700 mm in depth and 500 mm in diameter. Figure 4.1 illustrates the layout of the lysimeters and instrumentation at LDF, which is typical of the general layout of the other three lysimeter sites. LDF was the only site where the lysimeters were fenced off to prevent stock access.

Drainage water from the base of the lysimeters was directed to tipping bucket gauges (one per lysimeter) for the collection and measurement of the percolate (Figure 4.1). The tipping bucket drainage gauges were located within a collection pit near the lysimeters. To prevent edge flow, the preferential flow of water between the steel casing and the soil, liquefied petroleum jelly was injected around the inside lysimeter edge (Cameron et al., 1992). Rubber rims were also installed around the top of the lysimeters at LDF prior to the commencement of the experiment to prevent water from running off the top of the lysimeters, and around the PF lysimeters in December 2011 when it was thought that surface run-off was occurring. The rims extended 30 mm above the top of the steel casing and had a total freeboard of ~40 mm above the top of the soil (Plate 4.2). On the recommendation of T. Webb (see section 3.2.2), who identified the potential for restricted drainage from the PF and LDF lysimeters, fibreglass wicks were installed to create 0.5 m suction at the base of the lysimeters at the two sites (Plate 4.3).

Adjacent to the lysimeters at each site, an automatic tipping bucket rain gauge was installed at ground level by NIWA to measure inputs of irrigation and rainfall. Neutron probe access tubes were installed by HydroServices in the centre of each lysimeter (Figure 4.1) (Seyfried et al., 2001).
Figure 4.1 Larundel Dairy Farm lysimeter site layout plan showing the locations of the lysimeters and the tipping bucket collection systems.

Plate 4.1 Hand cut soil core with casing placement, Larundel Dairy Farm. Plate 4.2 Lysimeter L3 with rubber rims prior to installation in the ground, Larundel Dairy Farm.
Plate 4.3  Fibreglass wick installed at the base of a lysimeter, Pendo Farms.

4.2.2 Measurements

4.2.2.1 Rainfall, irrigation and drainage

Data logging and telemetry systems were set up at the TSD, PF and LDF sites, recording drainage from the lysimeter base and rainfall and irrigation inputs at 10-minute intervals.

Gaps in the lysimeter drainage data at LDF, TSD and PF occurred on several occasions due either to battery, logger, or network failure. These gaps were generally for only short periods (e.g. 20 minutes – 1 hour), and therefore drainage during these periods was assumed to be zero. At LDF, however, no drainage was recorded after 13/08/2012. At this time, the tipping bucket collection systems were removed due to high groundwater levels flooding the pit that housed the tipping buckets. Appendix 8 provides a summary of the dates and times where gaps occurred in the lysimeter drainage data.

4.2.2.2 Soil moisture

The volumetric soil moisture content (θ) of the lysimeters was measured using a combination of neutron probe and Time Domain Reflectometry (TDR) methods.

Neutron probe measurements were undertaken by HydroServices approximately weekly through the irrigation season (September-April) and every three to four weeks from May to August (Section 2.3.3.3). Measurements were taken at 150, 250, 350, 450, and 550 mm depths. The 150 mm depth measurements were taken to represent the water content from 0-200 mm, the 250 mm depth measurements from 200-300 mm, the 350 mm depth measurements from 300-400 mm, the 450 mm depth measurements from 400-500 mm, and the 550 mm depth measurements from 500-700 mm. The neutron probes were calibrated by Dr Tony Davoren of HydroServices. Calibration involved destructive sampling over a range of soil types around neutron probe access tubes for gravimetric analysis and bulk density determination. The measured volumetric water contents of the soil samples were used to calibrate the neutron probe (T. Davoren, pers. comm., 11 April 2013).
Because of the uncertainty surrounding neutron probe measurements in the upper 0-200 mm (Section 2.3.3.3), further measurements of the soil moisture were taken in the upper 150 mm using a portable TDR HydroSense probe (Campbell Scientific HydroSense, CS620) were taken.

During the 2012/2013 irrigation season, TDR soil moisture measurements were taken in the lysimeters in parallel with neutron probe measurements using 120 mm rods attached to the HydroSense probe. The measurements were timed to ensure a range of soil moisture contents was covered. HydroSense probe measurements were calibrated gravimetrically at each lysimeter site. The gravimetric method was used as it is the standard method for calibration (Reynolds, 1970) and involved field measurements of the volumetric water content using the HydroSense probe, followed by the collection of a soil core (minimum 50 mm diameter, approximately 120 mm deep). Three sets of HydroSense probe measurements and corresponding soil samples were collected during each field visit. In total a minimum of three field visits were completed for each lysimeter site. The collected soil cores were weighed, oven dried at 105°C for a minimum of 24 hours, and then reweighed. The soil moisture content as a percentage of the dry weight of the soil was then calculated. The soil moisture content was converted to a volumetric water content, using Equation 4.1:

\[ \theta = \left( w \times \frac{\rho_0}{\rho_w} \right) \times 150 \text{ mm} \]  \hspace{1cm} 4.1

were \( \theta \) is the volumetric water content of the soil, expressed as a percentage when multiplied by 100, \( w \) is the mass wetness (kg water/kg dry soil), \( \rho_0 \) is the dry bulk density of the soil, which is an expression of the ratio of the mass of solids to the total volume of the soil (kg/m³), and \( \rho_w \) is the density of water, 1,000 kg/m³ at standard temperature (Hillel, 1998). The values were multiplied by the 150 mm to get an equivalent water depth for the upper 150 mm of the soil profile.

The calibration equations, determined from the linear regression of the gravimetrically determined volumetric water contents against HydroSense probe measurements in the field at each site (Appendix 9), were used to adjust the lysimeter-based HydroSense measurements. Linear regression was then used to compare the calibrated HydroSense measurements with the 150 mm depth neutron probe measurements taken in the lysimeters (Appendix 10). These latter regression equations were applied to each of the 150 mm neutron probe measures over the experimental period, for each site.

4.2.3 Calculations

4.2.3.1 Actual evapotranspiration

AET was calculated for each of the nine lysimeters from measured rainfall and irrigation, lysimeter drainage, and changes in soil water storage between each successive soil moisture measurement. The water balance approach used was based on that given by Russell and Norman (1959), as follows:

\[ AET_{(t_2-t_1)} = R_{(t_2-t_1)} + I_{(t_2-t_1)} - D_{(t_2-t_1)} - RO_{(t_2-t_1)} - (\theta_{t_2} - \theta_{t_1}) \]  \hspace{1cm} 4.2
where between times \( t_1 \) and \( t_2 \) (days), rainfall (R) and irrigation (I) inputs were measured on-site (Section 3.2.3.1) and changes in soil water content (\( \theta \)) and drainage (D) from the lysimeters were recorded throughout the experiment. Surface water run-off (RO) was assumed zero at LDF due to the placement of rubber rims around the top of the lysimeters preventing surface redistribution of water (Section 4.2.1.1). Soil water flow modelling in HYDRUS was used to estimate the potential for surface water run-off at PF and TSD (Section 4.3.2.1).

At LDF, where drainage was not recorded after 13/08/2012 due to flooding of the pit that housed the drainage collection and recording system (Section 4.2.2.1), actual water use estimations were calculated using simulated drainage data (Section 4.3.2).

Estimations of daily AET (\( \text{AET}_{\text{daily}} \)) were calculated as follows:

\[
\text{AET}_{\text{daily}} = \left( \frac{\text{AET}_{(t_2-t_1)}}{\text{PET}_o(t_2-t_1)} \right) \times \text{Daily PET}_o
\]  

4.2.3.2 Crop coefficient time series

Crop coefficient (\( K_c \)) values were calculated for the nine lysimeters using Equation 2.37, over the same periods for which AET was calculated (i.e. between soil moisture measurements). Soil moisture measurements at each of the three sites were not taken on the same day as each other; therefore, to enable a like-for-like comparison among the sites, the \( K_c \) values were averaged to give mean monthly values throughout the experimental period.

4.2.3.3 Potential evapotranspiration

The PM\(_{\text{FAO}}\) equation (Equation 2.42) was used in the estimation of daily PET\(_o\) for each lysimeter site. The full PM equation (Equation 2.39), PT (Equation 2.43), DCC (Equations 2.44-2.46) and SWW (Equations 2.47-2.54) models were used to estimate daily PET\(_c\) at each of the three lysimeter sites. Calculation of FAO-PET\(_o\), PM-PET\(_c\) and DCC-PET\(_c\) followed the processes given in Allen et al. (1998). PT-PET\(_c\) and SWW-PET\(_c\) estimations followed the procedures given by Priestley and Taylor (1972) and Shuttleworth and Wallace (1985), respectively. Daily outputs of evapotranspiration from the DairyMod and HYDRUS models were also evaluated against the observed AET.

Daily pasture LAI and height data used in the PET\(_c\) calculations were the measured data for LDF (Sections 3.3.5 and 3.3.6) and simulated data for TSD and PF (Section 3.3.9). Climate data for the three sites were obtained from the on-site NIWA climate stations (Section 3.2.3). Where an estimate of the bulk stomatal resistance (\( r_1 \)) was required, a value of 100 s/m was assumed (Allen et al., 1998). Closed canopy and bare soil albedo values were assumed to be 0.23 (Allen et al., 1998) and 0.1 (Zhou et al., 2006), respectively. For the DCC model, daily percentage ground cover was estimated from daily LAI, based on the relationship between PAR interception and LAI (Figure 3.17), with the degree of PAR
interception taken to be equal to the ground cover. An empirical coefficient (α) value of 1.26 was assumed in the PT model, based on the findings of Jamieson (1982) (Section 2.4.2.2).

The effect of using measured and simulated pasture LAI and height data on PETₑ estimations was also assessed at LDF using the SWW model.

### 4.2.4 Soil water flow modelling in a field soil profile under ryegrass/white clover pasture

Soil water outputs from the DairyMod modelling carried out in Chapter 3 were firstly compared against the observed lysimeter drainage and soil moisture contents at TSD, PF and LDF. DairyMod, a biophysical model, incorporates all aspects of a dairy farm operation, including modules for pasture growth and utilisation by grazing animals, water and nutrient dynamics, animal physiology and production, and a range of options for pasture management, irrigation and fertiliser application (Section 2.3.2.6). The model is simplistic in its approach to soil water flow modelling compared with a more dynamic model such as HYDRUS-1D (Šimůnek et al., 2013) (HYDRUS), which numerically solves the Richards' equation (Equation 2.24) for variably saturated water flow. The performance of DairyMod was therefore also compared with outputs from HYDRUS for all three sites.

HYDRUS was firstly calibrated against lysimeter-measured drainage at Larundel Dairy Farm, West Eyreton, Canterbury. The model was then validated at the TSD and PF lysimeter sites against the measured lysimeter drainage and soil water content measurements.

#### 4.2.4.1 HYDRUS - Larundel Dairy Farm

The HYDRUS simulations assumed one-dimensional, uniform water flow through the 700 mm lysimeter soil profile. Each simulation was run for a period of 373 days from 07 September 2011 through to 14 September 2012, corresponding with the first and last soil moisture measurements taken over the experimental period.

The 700 mm deep soil profile within each pasture plot was separated into three layers, corresponding to soil water retention measurement depths given in Table 3.2. A uniform spatial discretization of Δx = 1 mm (701 nodes, 700 elements) was used for the model calculation grid.

The soil surface boundary condition involved actual daily precipitation (Section 3.2.3.1), which included irrigation, and potential evaporation and transpiration rates calculated using the SWW model. The SWW model was used as it enabled the two processes to be separated (Sections 2.4.2.4 and 4.3.5). Ponding was permitted on the surface to reflect the effect of the rubber rims installed around the top of the lysimeters (Section 4.2.1.1). The base of the lysimeter was simulated using a seepage face with a constant suction of 500 mm to represent the suction created by the wick (Section 4.2.1.1) (Sansoulet et al., 2008; van der Velde et al., 2005).
The van Genuchten-Mualem soil hydraulic model (van Genuchten, 1980) (Equation 2.32) was selected for the soil hydraulic properties. The soil hydraulic input parameters (coefficients $\alpha$ and $n$, the residual water content $\theta_r$, and the saturated water content $\theta_s$) were derived by fitting soil water retention data adjusted for stone content (Table 3.2) for each soil layer using the RETC package (version 6.02) (van Genuchten et al., 1991) (Section 2.3.3.4) (Pang et al., 2008; Sarmah et al., 2006). Mualem (1976) estimated the pore connectivity parameter $l'$ in the hydraulic conductivity function to average 0.5 for most soils. Saturated hydraulic conductivity ($K_{sat}$) was not measured on-site, and no estimates could be found in the literature, therefore, $K_{sat}$ values were estimated for each layer with Rosetta (Section 2.3.3.4) from soil textural and bulk density data (Appendix 1, Table 3.2) (Pang et al., 2008; Schaap et al., 2001). Table 4.1 provides a summary of the soil hydraulic parameters for each soil layer. Appendix 11 provides plots of the soil water retention curves at LDF.

Table 4.1  Saturated hydraulic conductivity estimated from soil textural and bulk density data and van Genuchten (1980) soil hydraulic parameters estimated using RETC from measured water retention data for a Darnley silt loam soil at Larundel Dairy Farm, Canterbury.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Depth (mm)</th>
<th>$\theta_r$ (mm$^3$/mm$^3$)</th>
<th>$\theta_s$ (mm$^3$/mm$^3$)</th>
<th>$\alpha$ (1/mm)</th>
<th>$n$</th>
<th>$l$</th>
<th>$K_{sat}$ (mm/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-180</td>
<td>0</td>
<td>0.43</td>
<td>0.00065</td>
<td>1.17</td>
<td>0.5</td>
<td>175</td>
</tr>
<tr>
<td>2</td>
<td>180-520</td>
<td>0</td>
<td>0.31</td>
<td>0.0092</td>
<td>1.11</td>
<td>0.5</td>
<td>77</td>
</tr>
<tr>
<td>3</td>
<td>520-700</td>
<td>0.03</td>
<td>0.18</td>
<td>0.0025</td>
<td>2.24</td>
<td>0.5</td>
<td>2002</td>
</tr>
</tbody>
</table>

Note: $\theta_r$ and $\theta_s$ are the residual and saturated water contents, $K_{sat}$ the saturated soil hydraulic conductivity, $l$ the tortuosity parameter in the conductivity function and $\alpha$ and $n$ parameters in the soil water retention function.

Root water uptake was simulated using the Feddes water uptake reduction model (Feddes et al., 2001; Feddes et al., 1978) (Section 2.3.3.4). Default root water uptake parameters in HYDRUS, suggested by Wesseling (1991), are given in Table 4.2. The critical stress water uptake index (or root adaptability factor) was set to zero to allow fully compensated root water uptake. The minimum allowed pressure head at the soil surface, below which soil evaporation is restricted, was set at the model default suction of -150 m (-1500 kPa).
Table 4.2  Default HYDRUS-1D root water uptake parameters for use in the Feddes et al. (1978) model, as given by Wesseling (1991).

<table>
<thead>
<tr>
<th>Feddes input parameters</th>
<th>Parameter value (Wesseling, 1991)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_1$ (mm)</td>
<td>-100</td>
</tr>
<tr>
<td>$h_2$ (mm)</td>
<td>-250</td>
</tr>
<tr>
<td>$h_{high}$ (mm)</td>
<td>-2,000</td>
</tr>
<tr>
<td>$h_{low}$ (mm)</td>
<td>-8,000</td>
</tr>
<tr>
<td>$h_4$ (mm)</td>
<td>-80,000</td>
</tr>
<tr>
<td>$T_{low}$ (mm/d)</td>
<td>5</td>
</tr>
<tr>
<td>$T_{high}$ (mm/d)</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: $h_1$ is the soil water pressure head at saturation and $h_4$ is the pressure head at the wilting point, above and below which water uptake ceases, respectively. $h_2$ and $h_3$ represent the soil water pressure heads between which water uptake is maximal. Below pressure head $h_3$, water uptake reduces and varies with the potential transpiration rate ($T$).

Sensitivity analysis overview

A sensitivity analysis was performed on a number of the assumed model variables, including the pasture rooting depth, soil hydraulic parameters $K_{sat}$ and $I$, the depth of ponding permitted at the surface, and on the assumed root water uptake parameters for the lysimeter-grown pasture at LDF.

Estimated $K_{sat}$ values from Table 4.1 and a value of 0.5 for the tortuosity parameter $I$ were initially assumed, as were the default root water uptake parameters given in Table 4.2. Parameters were adjusted according to the intervals specified in Table 4.3. The range tested for each of the parameters was based on a combination of the model default values, values reported in the literature and iterative adjustment of the parameters sufficient to allow a trend to be identified. Pasture rooting depths of 300-700 mm were assessed at 100 mm intervals. Within the literature rooting depths of 40-1100 mm have been reported for ryegrass pastures (Garwood & Sinclair, 1979; McKenzie et al., 1990; Parry et al., 1992; White & Snow, 2012). However, a maximum of 700 mm was used, as 700 mm was the base of the soil profile described in the model. The estimated pore-connectivity parameter $I$ and the $K_{sat}$ values were iteratively decreased and increased on a percentage basis, from 80-120% for $I$ and 50-150% for $K_{sat}$. The allowed ponding depth and the root water uptake parameters were also iteratively increased and decreased from the default values, as detailed in Table 4.3.

The sensitivity process involved manually altering a single parameter while all others were held constant, and iteratively running simulations. The simulated daily drainage below 700 mm was statistically compared with the average daily lysimeter drainage data using the NSE coefficient and NRMSD (Section 2.5). For each tested parameter, the value that gave the highest NSE coefficient and lowest NRMSD was selected. Table 4.3 and Appendix 12 provide a summary of the sensitivity analyses performed, and the resultant NSE and RMSD values. Typically, NSE >0.8 and NRMSD <0.2 is indicative of an accurate representation by the model of the observed data (Section 2.5). HYDRUS enables soil
hydraulic properties to be determined using an inverse solution function, however, when this was applied the model either wouldn’t converge, or if tolerances within the model were reduced to enable the model to converge, the solution was the initial input values given in Table 4.1. Accordingly, as with the DairyMod sensitivity analysis (Section 3.2.6.1), it is possible that a local rather than global optimum was achieved due to the incremental, iterative approach taken.

Table 4.3  Sensitivity analysis comparing different pasture rooting depths and soil hydraulic and root water uptake parameters in HYDRUS-1D drainage prediction simulations from irrigated, lysimeter-grown perennial ryegrass/white clover pasture at Larundel Dairy Farm, West Eyreton, Canterbury.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range tested</th>
<th>Change increments</th>
<th>NSE range</th>
<th>NRMSD range</th>
<th>Selected values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rooting depth</td>
<td>300 – 700</td>
<td>100</td>
<td>0.76 – 0.80</td>
<td>1.45 – 1.61</td>
<td>700</td>
</tr>
<tr>
<td>Soil hydraulic parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>l</td>
<td>0.80-1.20</td>
<td>0.05</td>
<td>0.80</td>
<td>1.45 – 1.46</td>
<td>1</td>
</tr>
<tr>
<td>Ksat (mm/d)</td>
<td>0.5 – 1.5</td>
<td>0.25</td>
<td>0.78 – 0.80</td>
<td>1.45 – 1.54</td>
<td>1</td>
</tr>
<tr>
<td>Ponding depth (mm)</td>
<td>0 – 25 mm</td>
<td>5</td>
<td>0.80</td>
<td>1.45</td>
<td>5</td>
</tr>
<tr>
<td>Root uptake parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>h1 (mm)</td>
<td>-350 – 0</td>
<td>100</td>
<td>0.80 – 0.83</td>
<td>1.32 – 1.45</td>
<td>-250</td>
</tr>
<tr>
<td>h2 (mm)</td>
<td>-400 – -250</td>
<td>50</td>
<td>0.83 – 0.84</td>
<td>1.31 – 1.32</td>
<td>-300</td>
</tr>
<tr>
<td>h3high (mm)</td>
<td>-5,000 – -1,000</td>
<td>1,000</td>
<td>0.84</td>
<td>1.31 – 1.32</td>
<td>-2,000</td>
</tr>
<tr>
<td>h3low (mm)</td>
<td>-10,000 – -6,000</td>
<td>1,000</td>
<td>0.84</td>
<td>1.31 – 1.32</td>
<td>-8,000</td>
</tr>
<tr>
<td>h4 (mm)</td>
<td>-90,000 – -60,000</td>
<td>10,000</td>
<td>0.84</td>
<td>1.31 – 1.32</td>
<td>-80,000</td>
</tr>
<tr>
<td>h5 (mm)</td>
<td>-150,000 – -90,000</td>
<td>20,000</td>
<td>0.84</td>
<td>1.31 – 1.32</td>
<td>-80,000</td>
</tr>
<tr>
<td>Tlow (mm/d)</td>
<td>0 – 3</td>
<td>1</td>
<td>0.84</td>
<td>1.31 – 1.32</td>
<td>5</td>
</tr>
<tr>
<td>Thigh (mm/d)</td>
<td>3 – 6</td>
<td>1</td>
<td>0.84</td>
<td>1.31 – 1.32</td>
<td>1</td>
</tr>
</tbody>
</table>

Note 1: Range tested refers to the relative values of the assessed parameters to the default parameters in Table 4.1.
Note 2: l is a tortuosity parameter and Ksat is the saturated hydraulic conductivity.
Note 3: h1 is the soil water pressure head at saturation and h4 is the pressure head at the wilting point, above and below which water uptake ceases, respectively. h2 and h3 represent the soil water pressure heads between which water uptake is maximal. Below pressure head h3, water uptake reduces and varies with the potential transpiration rate (T).

NSE is the Nash-Sutcliffe efficiency and NRMSD is the root mean square deviation normalised to the mean of the observed, used to compare the simulated and observed drainage from the 700 mm soil profile.

Results of the sensitivity analysis at LDF

NSE coefficients of 0.76-0.84 were achieved, alongside NRMSD values of 1.31-1.61 (Table 4.3, Appendix 12). The high NRMSD values compared with the reasonable NSE coefficients were due to the large range in daily (0-33 mm/d) observed drainage values and a number of zero, or near zero (i.e. <0.5 mm/d), drainage days (258 days), reducing the mean.

A rooting depth of 700 mm was found to provide the closest match between the observed and simulated drainage with an NSE of 0.80 and NRMSD of 1.45, which is greater than the 400 mm rooting depth identified for the lysimeters with DairyMod (Section 3.2.6.1). Changing the soil hydraulic parameter ‘l’ had a minor effect of 0.01 on the NRMSD but no effect on the NSE. The standard value
suggested by Mualem (1976) of 0.5 was therefore maintained. Changes to the estimated $K_{sat}$ values in Table 4.1 reduced the NSE and increased the NRMSD; therefore, the Table 4.1 values were used. Changes to the surface ponding depth also had no effect on the predictions, as infiltration was sufficient to prevent any ponding or surface run-off of water. Maintenance of the default root water uptake parameters in Table 4.2 resulted in the highest NSE coefficient (0.84) and lowest NRMSD (1.31 mm/d), except for $h_1$ and $h_2$, which each increased the NSE coefficient from 0.80-0.83 and from 0.83-0.84, respectively, when reduced to -250 and -350 mm from the default -100 and -250 mm values, respectively. While these changes are reasonably small, the criteria for selection of parameters were to increase the NSE and reduce the NRMSD. Therefore, the values that best met these criteria were selected.

**4.2.4.2 HYDRUS - Three Springs Dairies and Pendo Farms**

As at LDF, HYDRUS simulations at TSD and PF were run for 373 days from 07 September 2011 through to 14 September 2012.

The soil surface boundary condition at both sites involved actual daily precipitation, which included irrigation (Figure 3.2), and potential evaporation and transpiration rates calculated using the SWW model (Section 4.3.5). Unlike at LDF, water redistribution at the surface was permitted as rubber rims were not installed around the lysimeters at TSD or at PF until December 2011 (Section 4.2.1.1). The bases of the lysimeters were simulated using a seepage face. At PF a wick was installed at the lysimeter base so a constant suction of 500 mm was applied (Section 4.2.1.1) (Sansoulet et al., 2008; van der Velde et al., 2005). The same rooting depth of 700 mm and root water uptake parameters tested at LDF were applied at TSD and PF.

A range of data was available for estimation of the soil hydraulic parameters ($\alpha$, $n$, $\theta_r$, and $\theta_s$) used in the van Genuchten-Mualem model (Equation 2.32) and for the estimation of $K_{sat}$.

At TSD soil hydraulic data were determined by Dr Rogerio Cichota (pers. comm., 19 Dec. 2014) from a combination of on-site measurements and the use of pedotransfer functions (Cichota et al., 2013) to derive soil hydraulic properties for the lysimeter site (Appendix 13). The available data allowed for the Brooks and Corey (1964) model to be used (Equations 2.30 and 2.31) to obtain a series of points (pairs of soil matric potential and water content) (Appendix 14). These were then fitted to the van Genuchten-Mualem model using RETC (version 6.02) (van Genuchten et al., 1991) (Section 2.3.3.4). As at LDF, the pore connectivity parameter $l$ was set to 0.5 everywhere. Table 4.4 provides a summary of the estimated soil hydraulic parameters for each soil layer at TSD.
Table 4.4 Soil hydraulic parameters estimated for a Lismore silt loam soil at Three Springs Dairies, Methven, Canterbury.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Depth (mm)</th>
<th>$\theta_r$ (mm$^3$/mm$^3$)</th>
<th>$\theta_s$ (mm$^3$/mm$^3$)</th>
<th>$\alpha$ (1/mm)</th>
<th>$n$</th>
<th>$l$</th>
<th>$K_{sat}$ (mm/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-100</td>
<td>0.033</td>
<td>0.394</td>
<td>0.0050</td>
<td>1.18</td>
<td>0.5</td>
<td>10656</td>
</tr>
<tr>
<td>2</td>
<td>100-300</td>
<td>0.030</td>
<td>0.345</td>
<td>0.0022</td>
<td>1.20</td>
<td>0.5</td>
<td>3091</td>
</tr>
<tr>
<td>3</td>
<td>300-500</td>
<td>0.018</td>
<td>0.308</td>
<td>0.0024</td>
<td>1.23</td>
<td>0.5</td>
<td>2342</td>
</tr>
<tr>
<td>4</td>
<td>500-700</td>
<td>0.036</td>
<td>0.147</td>
<td>0.0047</td>
<td>1.53</td>
<td>0.5</td>
<td>12103</td>
</tr>
</tbody>
</table>

Note: $\theta_r$ and $\theta_s$ are the residual and saturated water contents, $K_{sat}$ the saturated soil hydraulic conductivity, $l$ the tortuosity parameter in the conductivity function and $\alpha$ and $n$ parameters in the soil water retention function.

Available data for PF included on-site textural and bulk density measurements (Appendix 3) and published water retention data for Templeton silt loam soils in Canterbury (Fraser et al., 1994; Watt & Burgham, 1992) (Appendix 15). Rosetta Lite, version 1.1 (Rosetta) (Schaap et al., 2001) (Section 2.3.3.4) was used to estimate the soil hydraulic parameters firstly from soil textural data and secondly from a combination of the soil textural and bulk density data. RETC (version 6.02) (van Genuchten et al., 1991) was used to predict soil hydraulic parameters from the soil water retention data published by Fraser et al. (1994) and Watt and Burgham (1992). Each of the resultant van Genuchten soil hydraulic parameter sets and saturated hydraulic conductivity values (Table 4.5) was tested in HYDRUS. The parameter set that resulted in the highest NSE coefficients and lowest NRMSD values when the measured average lysimeter drainage and soil moisture data were compared with the modelled outputs on a daily and then a weekly-fortnightly basis was selected. The results of the sensitivity analyses (Table 4.6) identified the data given by Watt and Burgham (1992) for the Templeton (2) and (3) soils to provide the highest NSE values and closest prediction of total drainage over the experimental period. The Templeton (2) soil hydraulic parameter and conductivity estimates were selected over the Templeton (3) estimates due to the fuller set of data available. Appendix 16 provides plots of the soil water retention curves at PF.

The high NRMSD values of 2.43-7.22 and 0.64-2.43 for the daily and weekly-fortnightly drainage data comparison in Table 4.6, respectively, when compared with the reasonable NSE coefficients, were due to the number of zero drainage days (312 days), reducing the observed mean.
Table 4.5  Saturated hydraulic conductivity and van Genuchten (1980) soil hydraulic parameters estimated from soil textual (%SSC) and bulk density data using Rosetta and from water retention data reported in the literature for a Templeton silt loam soil in Canterbury using RETC.

<table>
<thead>
<tr>
<th>Soil depth (mm)</th>
<th>(\theta_r) (mm(^3)/mm(^3))</th>
<th>(\theta_s) (mm(^3)/mm(^3))</th>
<th>(\alpha) (1/mm)</th>
<th>n</th>
<th>K(_{sat}) (mm/d)</th>
<th>l</th>
</tr>
</thead>
<tbody>
<tr>
<td>% SSC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-220</td>
<td>0.077</td>
<td>0.462</td>
<td>0.0006</td>
<td>1.61</td>
<td>127</td>
<td>0.5</td>
</tr>
<tr>
<td>221-400</td>
<td>0.077</td>
<td>0.462</td>
<td>0.0006</td>
<td>1.61</td>
<td>127</td>
<td>0.5</td>
</tr>
<tr>
<td>401-700</td>
<td>0.077</td>
<td>0.462</td>
<td>0.0006</td>
<td>1.61</td>
<td>127</td>
<td>0.5</td>
</tr>
<tr>
<td>%SSC + bulk density</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-220</td>
<td>0.076</td>
<td>0.455</td>
<td>0.0006</td>
<td>1.63</td>
<td>182</td>
<td>0.5</td>
</tr>
<tr>
<td>221-400</td>
<td>0.072</td>
<td>0.420</td>
<td>0.0006</td>
<td>1.63</td>
<td>86</td>
<td>0.5</td>
</tr>
<tr>
<td>401-700</td>
<td>0.070</td>
<td>0.406</td>
<td>0.0006</td>
<td>1.59</td>
<td>74</td>
<td>0.5</td>
</tr>
<tr>
<td>Watt and Burgham (1992): Templeton deep silt loam on sand (1)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-220</td>
<td>0.000</td>
<td>0.571</td>
<td>0.0500</td>
<td>1.15</td>
<td>2765</td>
<td>0.5</td>
</tr>
<tr>
<td>221-350</td>
<td>0.093</td>
<td>0.514</td>
<td>0.0034</td>
<td>1.37</td>
<td>79</td>
<td>0.5</td>
</tr>
<tr>
<td>351-700</td>
<td>0.000</td>
<td>0.482</td>
<td>0.0058</td>
<td>1.38</td>
<td>181</td>
<td>0.5</td>
</tr>
<tr>
<td>Watt and Burgham (1992): Templeton deep silt loam on sand (2)</td>
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<tr>
<td>0-220</td>
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<td>0.410</td>
<td>0.0016</td>
<td>1.15</td>
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<tr>
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<td>0.437</td>
<td>0.0232</td>
<td>1.11</td>
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<td>0.5</td>
</tr>
<tr>
<td>341-700</td>
<td>0.005</td>
<td>0.445</td>
<td>0.0042</td>
<td>1.17</td>
<td>85</td>
<td>0.5</td>
</tr>
<tr>
<td>Watt and Burgham (1992): Templeton deep silt loam on sand (3)</td>
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<td></td>
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<tr>
<td>0-190</td>
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<td>0.439</td>
<td>0.0029</td>
<td>1.13</td>
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<td>501-700</td>
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<td>0.0042</td>
<td>1.17</td>
<td>85</td>
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</tr>
<tr>
<td>Fraser (1992): Templeton deep silt loam</td>
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<td>0.468</td>
<td>0.0300</td>
<td>1.10</td>
<td>5880</td>
<td>0.5</td>
</tr>
<tr>
<td>251-450</td>
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<td>0.421</td>
<td>0.0278</td>
<td>1.11</td>
<td>2400</td>
<td>0.5</td>
</tr>
<tr>
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</tr>
<tr>
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<td>0.555</td>
<td>0.0009</td>
<td>1.85</td>
<td>24</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Note 1: No water retention data were given for the Templeton (3) soil (Watt & Burgham, 1992) below 500 mm, therefore the soil hydraulic parameters determined for Templeton (2) were assumed.

\(\theta_r\) and \(\theta_s\) are the residual and saturated water contents, K\(_{sat}\) the saturated soil hydraulic conductivity, l the tortuosity parameter in the conductivity function and \(\alpha\) and n parameters in the soil water retention function.
Table 4.6  Sensitivity analysis comparing different data source predictions of van Genuchten soil hydraulic parameters and saturated hydraulic conductivity values on estimations of daily drainage and soil moisture content with HYDRUS-1D at Pendo Farms (PF). Drainage values in brackets are the results of summed data compared on a weekly-two weekly basis (i.e. comparison of drainage accumulated between soil moisture measurements).

<table>
<thead>
<tr>
<th>Lysimeter Site</th>
<th>Data source</th>
<th>Drainage</th>
<th>Soil moisture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NSE</td>
<td>NRMSD</td>
</tr>
<tr>
<td>PF Templeton Silt Loam</td>
<td>Soil textural data</td>
<td>0.18 (0.76)</td>
<td>6.47 (2.32)</td>
</tr>
<tr>
<td></td>
<td>Soil textural + bulk density data</td>
<td>0.27 (0.75)</td>
<td>6.47 (2.32)</td>
</tr>
<tr>
<td></td>
<td>Watt and Burgham (1992) (1)</td>
<td>0.10 (0.90)</td>
<td>7.22 (1.51)</td>
</tr>
<tr>
<td></td>
<td>Watt and Burgham (1992) (2)</td>
<td>0.84 (0.98)</td>
<td>3.07 (0.64)</td>
</tr>
<tr>
<td></td>
<td>Watt and Burgham (1992) (3)</td>
<td>0.90 (0.91)</td>
<td>2.43 (1.44)</td>
</tr>
<tr>
<td></td>
<td>Fraser (1992)</td>
<td>0.68 (0.73)</td>
<td>4.31 (2.43)</td>
</tr>
</tbody>
</table>

NSE is the Nash-Sutcliffe efficiency, and NRMSD the normalised root mean square deviation, used to compare the simulated and observed profile drainage and soil moisture contents.

4.2.5 Statistical analysis

Statistical analysis of the data was conducted in GenStat (version 17, VSN International Ltd, 2013).

Despite the exclusion of L1 at LDF in the analysis of the pasture data (Chapter 4), it has been included in the analysis of water use data. The water use from L1 appeared lower than that from L2 and L3. However, the CV of the drainage among the three lysimeters at LDF was within the typical range for Canterbury (Section 4.4.1). Therefore, there was no basis for exclusion.

ANOVA procedures were used to statistically compare total accumulated lysimeter drainage and AET and monthly averaged mean daily AET rates between lysimeter sites. The effects of lysimeter site and month on monthly-derived crop coefficients were also assessed using ANOVA procedures. Where treatment means were significant ($\alpha=0.05$), they were separated using Fisher’s protected least significant difference (LSD) test. Unless otherwise specified, standard errors of the mean (SEM) were used to describe variation in the data within treatments.

An analysis of parallel lines was used to quantify and compare the WUE (slope of the regressions) and intercepts of herbage yield against AET at LDF, and then to compare the slopes and intercepts of the herbage yield against AET among the three lysimeter sites.

The NSE coefficient and RMSD, normalised to the mean of the observed data (Equations 2.55-2.57), were used to evaluate and compare the predictive abilities of DairyMod and HYDRUS for simulating soil water flow and each of the selected PETc models (PT, PM, DCC and SWW). The DairyMod and HYDRUS outputs were validated against measured lysimeter drainage (Sansoulet et al., 2008; van der Velde et al., 2005) and average soil profile water contents (Wöhling & Vrugt, 2007; Zhou et al., 2012).
Potential evapotranspiration estimations were compared against lysimeter AET. Simulated outputs that generated the highest NSE coefficient and lowest NRMSD were deemed to provide the best fit with the observed data.

To gain further insight into causes of the DairyMod and HYDRUS model deviations from the observed data, the MSD was partitioned into the squared bias (SB), non-unit slope (NU) and lack of correlation (LC), as given by Equations 2.58-2.61.

Where data are presented in tables, italicised font has been used to distinguish simulated results from measured data, for which normal font has been maintained.
4.3 Results

4.3.1 Lysimeter drainage and soil moisture

4.3.1.1 Measured drainage

Accumulated measured daily lysimeter drainage over the study period is presented in Figure 4.2 for the three lysimeter sites. Figure 4.3 presents the measured daily rainfall, irrigation, and drainage data for LDF, TSD and PF.

The total accumulated drainage between 07/09/2011 and 14/09/2012 from the LDF and TSD lysimeters (377±30.5 mm) exceeded (P=0.005) that from the PF lysimeters (108±30.5). Drainage from the TSD and LDF lysimeters equated to 39% of the total rainfall and irrigation inputs, compared with 11% from the PF lysimeters (P=0.005). The total lysimeter drainage recorded at LDF had a CV of 11% compared with 23% and 21% at TSD and PF, respectively. This variability is discussed in Section 4.4.1.

![Figure 4.2](image)

Figure 4.2 Accumulated daily lysimeter drainage at Larundel Dairy Farm (---), Three Springs Dairies (—) and Pendo Farms (—), for the period 07/09/2011-14/09/2012. The error bar shows the standard error of the mean of the total accumulated lysimeter drainage. Drainage data presented for Larundel Dairy Farm for the period 14/08/2012-14/09/2012 is the modelled lysimeter drainage (---) (Section 4.3.2).

Drainage was observed throughout the experiment from the LDF and TSD lysimeters following the occurrence of rainfall and/or irrigation. At PF, however, there were extended periods throughout the year of no drainage (Figures 4.2 and 4.3). Drainage was recorded only at the beginning of September 2011, during October 2011, and again throughout August and September 2012 at PF. No drainage occurred from mid-September to mid-October 2011 or from November 2011 through to August 2012. Of the 108±30.5 mm that drained, 87% (94 mm) was within a one-month period from 30/07/2012 to 02/09/2012 when 145 mm of rain fell.

Over the irrigation season, rainfall and irrigation inputs exceeded the PET<sub>o</sub> demand (Table 3.5) by ~105 mm at TSD. In contrast, at LDF and PF PET<sub>o</sub> demand was on average 112 and 215 mm greater than the...
total inputs of water. Accordingly, there was less drainage at PF compared with at LDF and TSD. On several occasions, the lysimeters at LDF and TSD were irrigated either just prior to, on the same day as, or shortly after, rainfall, which led to drainage (Figure 4.3). Of the total drainage measured, it was estimated that 41-66 mm (average of 53 mm) at LDF and 11-50 mm (average of 26 mm) at TSD occurred shortly after irrigation, suggestive of over-irrigation. At PF <0.1 mm of drainage occurred following irrigation.

![Graph showing daily rainfall, irrigation, and drainage from the base of the lysimeters at LDF, TSD, and PF from 07/09/2011 to 14/09/2012.](image)

**Figure 4.3** Stacked daily rainfall ( ■ ), irrigation ( ■ ) and drainage from the base of the lysimeters ( ■ ) at Larundel Dairy Farm (LDF), Three Springs Dairies (TSD) and Pendo Farms (PF) for the period 07/09/2011-14/09/2012. Drainage data presented for LDF for the period 14/08/2012-14/09/2012 are the modelled lysimeter drainage, the starting date for which is indicated ( ● ) (Section 4.3.2).
4.3.1.2 Soil moisture

Figure 4.4 provides a time series of the mean lysimeter volumetric soil moisture contents measured at 150 mm, 250 mm, 350 mm, 450 mm and 550 mm depths at LDF, TSD, and PF, relative to the soil moisture content at field capacity and at the critical capacity, below which pasture production is adversely affected.

The measured volumetric soil moisture content of the lysimeters at LDF remained at or just above field capacity throughout the study. While some variation in the water content did occur, primarily in the upper 0-200 and 200-300 mm layers, regular irrigation water inputs over the irrigation season (Figure 4.3) ensured the critical soil moisture content of ~17% was not reached (Section 3.2.2.1).

At TSD the soil moisture content of the lysimeters also remained near field capacity throughout the study period, except on two occasions during late December 2011 to mid-January 2012 and April 2012, where the soil water deficit reached 30% and 20% of the plant available water, respectively. However, the soil moisture was maintained above the critical level.

Despite irrigation and rainfall inputs throughout the study period, soil moisture deficits occurred at PF. The volumetric water content of the soil fell just below the critical level for approximately a one-week period mid-January 2012 and again for approximately two-weeks from early to mid-February 2012. However, 21.2 mm of rainfall on the 22/01/2012 and a series of smaller rainfall and irrigation events from the 18-23/02/2012 (Figure 4.3) increased the soil moisture above the critical deficit.

These results differ from the estimated actual soil moisture deficits calculated from the measured irrigation, rainfall and PET<sub>e</sub> data for each of the three sites (Figure 3.2), and therefore suggest that PET<sub>e</sub> over-estimated the actual evapotranspiration. This has been addressed in Section 4.3.5.
Figure 4.4  Mean lysimeter volumetric soil moisture content (%) with depth at Larundel Dairy Farm (LDF), Three Springs Dairies (TSD), and Pendo Farms (PF), for the period 24/08/2011-14/09/2012. Volumetric contents at field capacity ($\theta_{FC}$) and the critical capacity ($\theta_{L}$) are also shown. Total average $\theta_{FC}$ values for each of LDF, TSD and PF are 161, 192, and 239 mm, respectively, and total average critical capacity values for each site are 123, 144, and 174 mm, respectively. Stars (*) indicate the depths of soil moisture measurement, crosses (X) indicate measurement dates.
4.3.2 Simulated soil water flow with DairyMod and HYDRUS

4.3.2.1 Simulated drainage and surface water redistribution

Observed and DairyMod-simulated daily accumulated drainage over the experimental period at LDF, TSD and PF is shown in Figure 4.5. Figure 4.6 provides a residual analysis of drainage, summed between soil moisture measurement dates over the experiment for the three sites.

At LDF, DairyMod predicted the total drainage to be 362 mm for 07/09/2011-13/08/2012, a difference of 40 mm (12%) from the observed 322 mm. When drainage was compared on a daily basis, a NSE coefficient of 0.44 indicated a low-moderate fit between the simulated and observed data. However, when drainage data summed between soil moisture measurement dates (i.e. on a weekly to fortnightly basis) were compared, the fit improved with an NSE coefficient of 0.85 (Table 4.7). Similarly, the NRMSD decreased from 2.47 to 0.61. The high NRMSD values relative to the reasonable fit reflected by the NSE coefficients arose due to the large range in daily (0-33 mm/d) and weekly-fortnightly (0-58 mm) observed drainage values and a number of zero, or near zero (i.e. <0.5 mm/d), drainage days (258 days), reducing the mean. When the MSD was separated, the NU and SB were found to account for only 12 and 2% of the MSD, respectively, while 86% was due to a lack of correlation (Figure 4.6c).

At TSD, the DairyMod-simulated drainage totalled 658 mm, which equated to an over-estimate of 262 mm (66%) from that observed. This was reflected in lower NSE coefficients of 0.27 (daily) and 0.62 (weekly-fortnightly). The NRMSD values, when the simulated and observed data were compared on a daily (2.82) and weekly-fortnightly (1.12) basis were high. The persistent over-estimation of drainage throughout the experiment led to relatively high NU (36%) and SB (35%) components of the MSD (Figure 4.6f).

The total observed and simulated drainage at PF also differed, with DairyMod over-predicting the observed drainage of 108 mm by 99 mm (92%) (Figure 4.5). Over the experiment, 14 mm of the observed drainage occurred between the 19/10/2011 and 31/10/2011 following 55.8 and 10.8 mm rainfall events on the 19/10/2011 and 21/10/2011, respectively, compared with 36 mm predicted by DairyMod. The remaining 94 mm of the observed drainage occurred over the period 30/07/2012-02/09/2012 in response to a number of rainfall events ranging between <1.0 to >30 mm/d, and totalling 145 mm. For this same period, DairyMod predicted 125 mm of drainage. DairyMod also predicted drainage to occur on a number of occasions when no drainage was observed. However, despite these differences, the NSE coefficient achieved by DairyMod was high at 0.87 and 0.78 when the observed and simulated drainage data were compared on a daily and weekly-fortnightly basis, respectively. As at LDF and TSD, the large range in the observed drainage and numerous zero drainage days (312) reduced the observed mean, resulting in a high daily NRMSD of 2.66 and weekly-fortnightly NRMSD of 2.22 (Table 4.7).
Figure 4.5 Mean lysimeter observed (solid line) and DairyMod-simulated (dashed line) accumulated drainage below perennial ryegrass/white clover pastures at Larundel Dairy Farm (---), Three Springs Dairies (—) and Pendo Farms (—) for the period 07/09/2011-14/09/2012. No drainage was recorded for the period 14/08/2012-14/09/2012 at LDF, the starting date for which is indicated (•).
Figure 4.6  Residual analysis of observed and DairyMod-simulated lysimeter drainage below perennial ryegrass/white clover pastures at Larundel Dairy Farm (▲) (LDF), Three Springs Dairies (◆) (TSD) and Pendo Farms (●) (PF), for the period 07/09/2011-14/09/2012. No drainage was recorded for the period 14/08/2012-14/09/2012 at LDF. Plots show the relationship between the observed and simulated drainage where solid lines (―) show the 1:1 relationship and dotted lines (---) are the fitted lines (left), residuals (simulated-observed) over time (centre) and the segmentation of the MSD into the squared bias (□), the non-unit slope (■, ■, ■) and the lack of correlation (■, ■, ■) (right). Forms of the fitted lines are: (a) $y = (0.88 \pm 0.06)x + 0.36 \pm 1.22$ ($r^2=0.87$), (d) $y = (0.72 \pm 0.04)x – 2.06 \pm 1.33$ ($r^2=0.89$), and (g) $y = (0.80 \pm 0.05)x – 1.50 \pm 0.85$ ($r^2=0.87$).
Table 4.7  Summary statistics indicating DairyMod and HYDRUS performance in the prediction of lysimeter drainage, between successive soil moisture measurements, and soil moisture content at Larundel Dairy Farm, Three Springs Dairies and Pendo Farms for the period 07/09/2011-14/09/2012. CV is the coefficient of variation, NSE is the Nash-Sutcliffe efficiency, and RMSD and NRMSD are the standard and normalised root mean square errors, respectively. Drainage values for Larundel Dairy Farm relate to the period 07/09/2011-13/08/2012.

<table>
<thead>
<tr>
<th>Site</th>
<th>Summary Statistic</th>
<th>Drainage (mm)</th>
<th></th>
<th>Soil moisture content (%)</th>
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<td></td>
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<td>DairyMod</td>
<td>Observed</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Simulated</td>
<td>Bias</td>
<td>Simulated</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Larundel Dairy Farm</td>
<td>Maximum (mm/d, %)</td>
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<td>30.4</td>
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<td>30.1</td>
</tr>
<tr>
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<td>Minimum (mm/d, %)</td>
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<td>0.0</td>
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<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Mean (mm/d, %)</td>
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<td>0.1</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>CV (mm)</td>
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<td>362</td>
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<td></td>
</tr>
<tr>
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<td>Maximum (mm/d, %)</td>
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<td>47.0</td>
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<td>Minimum (mm/d, %)</td>
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<td>NSE</td>
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<td>RMSD (mm, %)</td>
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<td>6.59</td>
<td>-</td>
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<td>NRMSD</td>
<td>-</td>
<td>0.70</td>
<td>-</td>
<td>0.61</td>
</tr>
<tr>
<td>Three Springs Dairies</td>
<td>Maximum (mm/d, %)</td>
<td>37.0</td>
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<td>-11.5</td>
<td>34.2</td>
</tr>
<tr>
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<td>Minimum (mm/d, %)</td>
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</tr>
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<td>Mean (mm/d, %)</td>
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<td>0.1</td>
<td>0.6</td>
</tr>
<tr>
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<td>Sum (mm)</td>
<td>108</td>
<td>131</td>
<td>23</td>
<td>207</td>
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<tr>
<td></td>
<td>CV (%)</td>
<td>725</td>
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<td></td>
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<td>NSE</td>
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<td>0.78</td>
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<td>RMSD (mm, %)</td>
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<td>-</td>
<td>6.30</td>
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<tr>
<td></td>
<td>NRMSD</td>
<td>-</td>
<td>0.64</td>
<td>-</td>
<td>2.22</td>
</tr>
</tbody>
</table>
Observed and HYDRUS-simulated daily accumulated drainage over the experimental period at LDF, TSD and PF is shown in Figure 4.7. Figure 4.8 provides a residual analysis of drainage data, summed between soil moisture measurement dates over the experiment, for the three sites.

At LDF, HYDRUS predicted the total drainage to be 349 mm, 27 mm (8%) more than that observed for the period 07/09/2011-13/08/2012 (Figure 4.7). This was an improvement of 4% from that simulated by DairyMod. The HYDRUS-simulated daily drainage followed the measured drainage closely. There were eight drainage events where the observed exceeded 10 mm/d. For six of the eight, the simulated drainage was within 1.4-2.8 mm (5-24%) of the observed. For the remaining two events of 11 and 15 mm (09/11/2011 and 10/11/2011), the simulated drainage was within 6 and 9 mm of the observed. The result was a low mean daily bias of 0.1 mm, an NSE coefficient of 0.84 and NRMSD of 1.45 (Table 4.7). When summed between soil moisture measurement dates (i.e. on a weekly-fortnightly basis), the NSE was 0.81 and NRMSD of 0.70. As with the DairyMod results, the high NRMSD values were caused by the large range in observed drainage values and the 258 days of zero or near zero drainage, reducing the observed mean (Table 4.7). When compared with the DairyMod results, the residual analyses indicated a reduction in the LC component of the MSD from 86% to 53%, represented by a higher $r^2$ with HYDRUS. However, the NU component increased and was reflected in a slope further from one of 0.76±0.05 compared with 0.88±0.06 for DairyMod.

HYDRUS-simulated drainage at TSD also followed the pattern of the observed, although, as with DairyMod, HYDRUS persistently over-estimated drainage (Figure 4.8d-e). For example, there were 10 drainage events where the observed exceeded 10 mm/d. However, HYDRUS-simulated 18 drainage events of 10 mm/d or greater. Over the experimental period, HYDRUS predicted the total drainage to be 617 mm, 221 mm (56%) more than the observed (Figure 4.7), which was an improvement on the 658 mm predicted by DairyMod. The NSE coefficient of 0.73, when the simulated and observed drainage were compared on a weekly-fortnightly basis, and NRMSD of 0.95 indicated an improved fit when compared with DairyMod (Table 4.7). The lack of agreement by both DairyMod and HYDRUS with the observed data is discussed in Section 4.3.2.2.

HYDRUS also over-estimated the total drainage at PF. Over the experiment, HYDRUS-simulated a total of 131 mm of drainage compared with the observed 108 mm, a difference of 23 mm (21%) (Figure 4.7). However, this provided a 70% improvement on that simulated with DairyMod (Table 4.7). The NSE coefficient achieved by HYDRUS was high at 0.84 and 0.98 when the observed and simulated drainage data were compared on a daily and weekly-fortnightly basis, with NRMSD values of 3.07 and 0.64, respectively (Table 4.7). HYDRUS also led to a reduction in the SB and NU components of the MSD, with a majority (90%) attributable to a lack of correlation, and a higher $r^2$ of 0.98 was achieved compared with the DairyMod results (0.87).
No run-off was predicted from the PF or TSD lysimeters, and run-off at LDF was prevented by the rubber rims installed around the top of the lysimeters (Section 4.2.1.1).

Figure 4.7  Mean lysimeter observed (solid line) and HYDRUS-simulated (dashed line) daily accumulated drainage below perennial ryegrass/white clover pastures at Larundel Dairy Farm (—) (LDF), Three Springs Dairies (—) and Pendo Farms (—) for the period 07/09/2011-14/09/2012. No drainage was recorded for the period 14/08/2012-14/09/2012 at LDF, the starting date for which is indicated (▼).
Figure 4.8 Residual analysis of observed and HYDRUS-simulated lysimeter drainage below perennial ryegrass/white clover pastures at Larundel Dairy Farm (▲) (LDF), Three Springs Dairies (●) (TSD) and Pendo Farms (●) (PF), for the period 07/09/2011-14/09/2012. No drainage was recorded for the period 14/08/2012-14/09/2012 at LDF. Plots show the relationship between the observed and simulated drainage where solid lines (—) show the 1:1 relationship and dotted lines (---) are the fitted lines (left), residuals (simulated-observed) over time (centre) and the segmentation of the MSD into the squared bias (□), the non-unit slope (■, ■, ■) and the lack of correlation (■, ■, ■) (right). Forms of the fitted lines are: (a) \(y = (0.76 \pm 0.05)x + 1.93 \pm 1.04 \left( r^2 = 0.90 \right) \), (d) \(y = (0.72 \pm 0.02)x - 1.37 \pm 0.74 \left( r^2 = 0.96 \right) \), and (g) \(y = (1.01 \pm 0.02)x - 0.62 \pm 0.30 \left( r^2 = 0.98 \right) \).

4.3.2.2 Simulated drainage – further investigation

Differences are evident between the observed and simulated (DairyMod and HYDRUS) drainage at TSD and PF. These differences arose in response to physical restrictions of the lysimeters preventing redistribution of water on to the lysimeters from the surrounding pasture. Rather, the lysimeters facilitated the run-off of water only (discussed below). Accordingly, with the run-off of water but no run-on, the total water infiltrating the soil profile was reduced, which in turn reduced the potential for
drainage from the lysimeters. The models, however, translated this loss of water from the lysimeter surface as drainage, as no restrictions such as those created by the lysimeters existed within the models, and is likely representative of what would have occurred under standard paddock conditions (Section 4.4.2). This was highlighted at LDF where a close fit was achieved between the observed and simulated drainage due to the rubber rims installed around the top of the lysimeter casings, preventing run-off (Figure 4.5). Similarly, at PF, when the drainage was separated and compared with that modelled pre- and post-installation of the rubber rims in December 2011, pre-installation, the models over-estimated the observed drainage but post-installation, a closer fit was achieved (Figure 4.9). DairyMod over-estimated drainage by 31 mm (214%) before and 67 mm (72%) after the rubber rims were installed. HYDRUS over-estimated the drainage pre-rim installation by 13 mm (90%). Once the rims were installed, the drainage predicted by HYDRUS was within 10 mm (10%) of that observed. Accordingly, the degree of over-estimation reduced once the rims were in place. The closer fit in modelled and observed drainage at LDF and at PF, once the rubber rims were installed, provided some indication that the lack of rubber rims at TSD may have led to the over-estimation of the observed drainage by the models at TSD.

At PF and TSD, a build-up of organic material in the lysimeters over time is considered to have prevented redistribution of water onto the lysimeters from the surrounding pasture, but enabled run-off (Section 4.4.2). Plate 4.4 illustrates the change in the lysimeter surface at TSD. At the time of installation the tops of the lysimeter casings were positioned just above (~10 mm) the ground surface (Section 4.2.1.1). Over time, organic material built up to the point where the rims were nearly completely covered, and the difference in the surface level of the lysimeter with that of the surrounding ground was up to 10 mm. When rain fell in excess of the infiltration capacity of the soil, water ran off the lysimeter surfaces, but was prevented from running on. Accordingly, the measured lysimeter drainage was lower than the potential. Figure 4.10 presents the estimated potential drainage through the lysimeters. At TSD the potential drainage totalled 617 mm and at PF it totalled 121 mm. This is discussed further in Section 4.4.2.2.

Overall, the HYDRUS model was deemed to be a more accurate predictor of drainage, and able to represent drainage under standard field conditions, although predictions with DairyMod were also reasonable.
Figure 4.9  Mean lysimeter observed drainage (---) and HYDRUS (----) and DairyMod (—) simulated drainage, accumulated over the periods 07/09/2011-30/11/2011 and 01/12/2011-14/09/2012 at Pendo Farms. The approximate date at which the rubber rims were installed around the top of the lysimeters is indicated (†).

Plate 4.4  Lysimeter core L3 at Three Springs Dairies showing (a) the top of the steel casing extended just above the soil surface on installation (May 2010) (source: M Flintoft, Aqualinc Research Limited) and changes at the lysimeter surface August 2013 (b) and May 2014 (c) where the lysimeters tops have been covered by a build-up in organic material over time.
Figure 4.10 Accumulated potential drainage at Three Springs Dairies (---) and Pendo Farms (--), for the period 07/09/2011-14/09/2012. At PF, HYDRUS-simulated drainage data were used up until December 2011 (--), after which point rubber rims were installed and the measured drainage was used (---). At TSD, the data presented are the HYDRUS-simulated drainage data. Periods where simulated drainage was used are represented for each site by the dashed lines.

4.3.2.3 Simulated soil moisture

As with the observed soil moisture data, DairyMod maintained the soil moisture at LDF and TSD at or near field capacity, due to the influence of irrigation (Figures 4.11a and 4.11d). However, at LDF, there was a persistent bias where the simulated soil moisture was, on average, 5.2% drier than the observed (Figures 4.11b), resulting in high NU values of 95% (Figures 4.11c). The calculated NSE coefficient was less than zero, indicative that the average of the observed data was a more accurate predictor than the model. This occurred due to limitations with the NSE coefficient (Section 2.5), whereby the CV of the observed data was small at 3%, therefore the NRMSD was also calculated and indicated a strong match at 0.19 (Table 4.7).

At TSD, the simulated SMC closely followed the observed, with a mean daily bias of 1.5%. As at LDF, the low 6% CV of the observed data resulted in an NSE of 0.17. However, the small NRMSD of 0.05 indicated a strong fit between the data. When compared with the results at LDF, there was a greater component of the MSD attributable to a general lack of correlation (66%) (Figure 4.11f).

At PF, the DairyMod-simulated soil moisture did not reach the same soil moisture deficits as what was observed, with soil moisture contents ranging between 28.1% and 39.2% compared with the observed range of 24.5-36.9% (Figure 4.11h). Again the small variation in the observed soil moisture content (CV=13%) meant that the NSE coefficient was less than zero but the NRMSD was indicative of a reasonable match at 0.13. As with TSD, a lack of correlation was the cause of a majority (74%) of the MSD.
Figure 4.11  Residual analysis of observed and DairyMod-simulated soil moisture content (SMC) to 700 mm depth below perennial ryegrass/white clover pastures at Larundel Dairy Farm (▲) (LDF), Three Springs Dairies (◆) (TSD) and Pendo Farms (●) (PF), for the period 07/09/2011-14/09/2012. Plots show the relationship between the observed and simulated yields where solid lines (—) show the 1:1 relationship, dotted lines (---) are the fitted lines (left), the simulated (----) and observed (symbols) SMC over time, with the soil moisture content at field capacity, the critical level and wilting point indicated by the upper, mid and lower horizontal grey lines, respectively (centre), and the segmentation of the MSD into the squared bias (□), the non-unit slope (■, ■, ■) and the lack of correlation (■, ■, ■) (right). Forms of the fitted lines are: (a) $y = (0.37±0.05)x + 19.67±1.14$ ($r^2=0.66$), (d) $y = (1.04±0.19)x – 0.19±5.13$ ($r^2=0.46$), and (g) $y = (0.97±0.29)x – 1.06±9.27$ ($r^2=0.24$).

The same general trends in the observed SMC were simulated in HYDRUS for the lysimeters at LDF. Over the experimental period, the soil moisture was maintained at or near field capacity, due to the influence of irrigation (Figure 4.12a). On average, HYDRUS predicted the soil moisture to be 1.7% (~12 mm) drier than the observed, an improvement of 3.5% compared with that simulated with DairyMod. However, the calculated NSE coefficient was again less than zero due to a low coefficient of variation.
of 3% (Table 4.7), but the NRMSD of 0.07 was indicative of a strong fit. The mean bias of the simulated data led to SB contributing 77% of the MSD, although this was less than the 95% simulated by DairyMod (Figure 4.11c).

At TSD, there was a persistent bias whereby the HYDRUS-simulated soil moisture was 3.4% drier than the observed and 2.7% drier than the bias simulated with DairyMod (Table 4.7, Figure 4.12e). However, both the observed and simulated SMC values were maintained near field capacity throughout the experiment excluding a period from 20/12/2011 to 18/01/2012 where the simulated soil moisture approached, but did not fall below, the critical level. Overall, neither the observed nor the simulated soil water at TSD resulted in limiting conditions to pasture growth. As with LDF, the NSE coefficient was less than zero due to a small coefficient of variation (6%). However, the NRMSD was low at 0.13, indicative of a reasonable fit between the observed and simulated data (Table 4.7), but higher than the NRMSD of 0.05 achieved with DairyMod.

Differences between the observed and HYDRUS-simulated soil moisture contents at PF were 2.2% on average (Table 4.7), and differed from the DairyMod simulations by only 0.2%. The NSE coefficient represented a strong fit between the observed and simulated data at 0.62. The NRMSD was estimated to be 0.08.

The simulated drainage and soil moisture by HYDRUS and DairyMod were comparable. However, HYDRUIS was found to be overall superior in the estimation of drainage and soil moisture across the three sites. A discussion of the reasons for the differences among the observed and HYDRUS and DairyMod-simulated soil moisture contents is given in Section 4.4.2.3.
Figure 4.12  Residual analysis of observed and HYDRUS-simulated soil moisture content (SMC) to 700 mm depth below perennial ryegrass/white clover pastures at Larundel Dairy Farm (▲) (LDF), Three Springs Dairies (◆) (TSD) and Pendo Farms (●) (PF), for the period 07/09/2011-14/09/2012. Plots show the relationship between the observed and simulated soil moisture contents where solid lines (—) show the 1:1 relationship and dotted lines (---) are the fitted lines (left), the simulated (—) and observed (symbols) SMC over time, with the soil moisture content at field capacity, the critical level and wilting point indicated by the upper, mid and lower horizontal grey lines, respectively (centre), and the segmentation of the MSD into the squared bias (□), the non-unit slope (■, ■, ■) and the lack of correlation (■, ■, ■) (right). Forms of the fitted lines are: (a) y = (0.44±0.07)x + 16.54±1.83 (r²=0.58), (d) y = (0.86±0.07)x + 6.85±1.65 (r²=0.82), and (g) y = (0.91±0.05)x – 0.76±1.49 (r²=0.92).

4.3.3 Pasture water use

4.3.3.1 Actual evapotranspiration

Annually, the AET calculated using Equation 4.2 was 776±29.3 at TSD, 717±29.3 at PF and 615±29.3 at LDF (p=0.043), but a difference (p<0.005) only existed between TSD and LDF (Figure 4.13a). Where the measured drainage was replaced with the potential drainage at PF and TSD (Figure 4.10), the annual
AET reduced to 704±19.8 at PF and 554±19.8 at TSD (Figure 4.13b). The change at PF was smaller (13 mm) compared with that at TSD (222 mm), as there was only a short period during the experiment (September-November 2011, inclusive) where no rims were installed at PF, whereas at TSD there were no rubber rims around the tops of the lysimeters for the duration of the experiment.

There were no differences (0.067<P<0.954) in the mean daily AET estimated with the observed drainage (AET_{obs}) among the three sites in October 2011 and January, February, June and July 2012 (Figure 4.14a). When the potential drainage data were used in the AET_{daily} calculations at PF and TSD (AET_{pot}) (Figure 4.10), there were no differences (0.072<P<0.536) among the three sites in October 2011 and December, March, April, July and August 2012 (Figure 4.14b). The effect of lysimeter site was significant (0.001<P<0.040) during all other months. The three sites followed a typical seasonal pattern with rates peaking during spring and summer and reducing through autumn to their lowest in winter.

With measured drainage data, TSD had the highest (P=0.013) monthly averaged AET_{daily} rate of 4.07±0.142 mm/d in December 2012. The lowest AET_{daily} rate was 0.47±0.234 at PF (P=0.037) in August 2012, followed by 0.51±0.102 at all three sites (P=0.954) in July 2012. With the potential drainage data, monthly averaged AET_{daily} rates ranged from 3.71±0.047 in January 2012 at PF to 0.07±0.106 in June 2012 at TSD. Full details of the AET_{daily} for the three lysimeter sites, with treatment effects, are given in Appendix 17.

Figure 4.13 Accumulated actual evapotranspiration (AET) calculated using Equation 4.2 with measured drainage (a) and potential drainage (b) data for perennial ryegrass/white clover pastures at Larundel Dairy Farm (―), Three Springs Dairies (―) and Pendo Farms (―), for the period 07/09/2011-14/09/2012. Error bars show the maximum SEM for the effects of lysimeter site. LDF excluded from (b) as rims were installed around the tops of the lysimeters throughout the experiment, preventing redistribution of water at the soil surface.
Figure 4.14 Monthly averaged mean daily actual evapotranspiration (AET$_{daily}$) calculated using Equations 4.2 and 4.3 with measured drainage data (a) and potential drainage (b) data for perennial ryegrass/white clover pastures at Larundel Dairy Farm (▲), Three Springs Dairies (◆) and Pendo Farms (●) for September 2011 to September 2012. Error bars show the maximum SEM for the effects of lysimeter site. LDF excluded from (b) as rims were installed around the tops of the lysimeters throughout the experiment, preventing redistribution of water at the soil surface.

4.3.3.2 Water use efficiency

When measured drainage was used in the calculation of AET (AET$_{obs}$), the WUE of lysimeters L2 and L3 at LDF was 14.5±0.64 kg DM/ha/mm (P=0.571) for 09/07/2011-07/09/2012 (Figure 4.15a). The WUE of the lysimeter-grown pasture for the same period at TSD, with simulated yields, was 15.3±0.46 kg DM/ha/mm. At PF, the WUE was estimated to be 20.6±0.94 kg DM/ha/mm. An analysis of parallel lines identified no differences (P=0.435) in the slopes (i.e. the WUE) at TSD and LDF.

Where the measured drainage data were replaced with the estimated potential drainage data in the AET calculations at PF and TSD (AET$_{pot}$) (Figure 4.13), the WUE was 20.2±0.66 at TSD and PF (P=0.938), with no differences (P=0.250) in the y-axis intercept of 279±270 kg DM/ha (Figure 4.15b).

The WUE of the pastures for each regrowth cycle was determined to see how WUE differed over the irrigation season (Figure 4.16). The WUE of the ryegrass pastures at each site followed a similar seasonal trend of higher efficiencies early to mid-spring, followed by a reduction in summer and then an increase into autumn and through winter. At LDF, the WUE at the end of the first regrowth cycle was more than twice that at TSD and PF and was probably due to a combination of seed head development following seven weeks of growth for silage (Section 3.3.2) and the remobilisation of underground reserves (Section 4.4.3). The reduction in WUE during the summer coincided with a slump in pasture growth and higher temperatures. This is discussed further in Section 4.4.3.
Figure 4.15  Accumulated total herbage yield against (a) accumulated actual evapotranspiration calculated from measured lysimeter drainage data (AET_{obs}) and (b) accumulated AET calculated using the estimated potential drainage data (AET_{pot}) (Figure 4.13) of perennial ryegrass/white clover pastures at Larundel Dairy Farm (▲) (LDF), Three Springs Dairies (▼) (TSD) and Pendo Farms (●) (PF), for the periods 09/09/2011-07/09/2012. DairyMod-simulated herbage yield data were used for TSD and PF (Figure 3.25). Forms of the fitted lines for (a) are y = (14.5±0.64)x + 2232±244 (r²=0.98) (LDF), y = (15.3±0.46)x + 565±222 (r²=0.99) (TSD), y = (20.6±0.94)x - 357±434 (r²=0.98) (PF), and for (b) are y = (20.2±0.66)x + 279±270 (r²=0.98) (TSD and PF). Treatment mean for the lysimeters at LDF excluded L1.

Figure 4.16  Water use efficiencies (WUE) (kg DM/ha/mm) calculated with AET (Figure 4.13) determined using measured drainage (a) and estimated potential drainage (b) data for ryegrass-based pastures at Larundel Dairy Farm (▲), Three Springs Dairies (▼) and Pendo Farms (●) for the period 09/09/2011-07/09/2012. WUE values were calculated for each regrowth cycle, based on the start and end dates at Larundel Dairy Farm (Table 3.6).

4.3.4 Crop coefficients

With AET estimates using the observed drainage data at TSD and PF, for irrigation season months October 2011 and January, February, April and September 2012 there were no differences (0.054<P<0.142) in the mean monthly Kc values among the three sites, averaging 0.85±0.043, 0.85±0.042, 0.81±0.028, 0.70±0.021 and 0.69±0.018, respectively (Figure 4.17a). Similarly, outside of
the irrigation season there were no differences in June and July (0.197<P<0.992) with monthly averaged \( K_c \) values of 0.80±0.1128 and 0.585±0.1165, respectively. For all other months, differences in \( K_c \) were significant among sites (0.007<P<0.044). Ranges in \( K_c \) values within sites were 0.56-0.78 for LDF, 0.59-0.89 for TSD and 0.74-1.11 for PF (P<0.001).

Differences in \( K_c \) among and within lysimeter sites with month led to no systematic pattern observed in the data and a site\(*\)month interaction (P<0.001), which accounted for 35% of the total sum of squares (SS\(_T\)). For example, the \( K_c \) was 1.13±0.112 in December 2011 and February and August 2012 at TSD and June 2012 at PF. Meanwhile, for the same months, the \( K_c \) averaged 0.86±0.112 at PF in December 2011 and LDF in June 2012, 0.78 at LDF in December 2011 and February 2012, and was 0.59±0.112 at PF in February 2012, 0.50±0.112 at TSD in June 2012, and 0.43±0.112 at LDF and 0.39±0.112 at PF in August 2012.

When the estimated potential data were used in place of measured data at TSD and PF (Figure 4.17b), the results were comparable to the results using the observed AET with a site\(*\)month interaction (P<0.001) that accounted for 39% of the SS\(_T\). At TSD, the irrigation season monthly \( K_c \) values ranged from 0.42-0.92 and at PF they were 0.43-0.94.

Based on these results a single \( K_c \) value representative of the three sites was not able to be determined with either set of \( K_c \) time series, and neither was a single time series of monthly averaged mean daily values. The implications of these results and reasons for the observed differences are discussed in Section 4.4.4.

As a check on the effectiveness of the measured AET data for determining \( K_c \) values, daily SWW-PET\(_C\) data (Section 4.3.5) were converted to \( K_c \) values, by dividing by the daily FAO-PET\(_C\) values for each site. For each site, a daily \( K_c \) time series was developed, which was then converted to a monthly time series.
(Figure 4.18). By doing so, much of the variability among the sites evident in the $K_c$ time series in Figure 4.17 was eliminated. Previously, the monthly coefficients of variation ranged from 3-76%, when $K_c$ values for the three sites were compared. With $K_c$ determined from the SWW data, the coefficients of variation reduced to 2-23% over the year. The greatest variation occurred during the winter months, which are not relevant to the estimation of water use over the growing/irrigation season.

**Figure 4.18** Daily and monthly averaged mean crop coefficients ($K_c$) calculated as a ratio of daily Shuttleworth-Wallace potential crop evapotranspiration (SWW-PET$_c$) to the reference crop potential evapotranspiration (FAO-PET$_o$) for perennial ryegrass/white clover pasture at Larundel Dairy Farm (—), Three Springs Dairies (—) and Pendo Farms (—) for September 2011 to September 2012.

From a water resource management perspective, a single $K_c$ time series applicable across the Canterbury Plains would provide the most practical approach to estimating actual water demand ($K_c$ PET$_c$), for which a mean of the three sites’ $K_c$ time series, determined using SWW-PET$_c$ (Figure 4.18) is considered to provide a reasonable estimate. The sensitivity of water use estimation over the irrigation season in Canterbury, based on using the SWW-based $K_c$ time series ($K_{cSWW}$), has therefore been analysed.

Over the experimental period, the $K_{cSWW}$ time series provided a reasonable method of estimating water use across all three sites. Total AET was 9 mm (1%) less than that predicted at LDF (Table 4.8). At TSD, AET$_{pot}$ was 50 mm (9%) less, and at PF, the difference between AET$_{pot}$ and $K_{cSWW}$-PET$_c$ was 60 mm (8%). The NSE coefficients and NRMSD of the residuals in Table 4.8 indicated a reasonable fit between the observed and simulated data for the three sites.

The $K_{cSWW}$-PET$_c$ predictions were compared with predictions of PET$_c$ using alternative $K_c$ time series illustrated in Figure 4.19. Time series considered included the lysimeter site averaged time series developed from AET$_{obs}$ ($K_{cAETobs}$) and AET$_{pot}$ ($K_{cAETpot}$), a time series developed from the ‘initial’ and ‘mid’ $K_c$ values in Allen et al. (1998), for which an average of the given ‘mid’ stage $K_c$ values of 0.95 was assumed ($K_{cFAO}$), and the time series developed by Bright (2009a) ($K_{cBright}$). The derived $K_{cSWW}$-PET$_c$ estimations were comparable to the estimations using the lysimeter site averaged $K_{cAETpot}$ time series.
(Table 4.8). Both methods generated total PET\textsubscript{c} predictions within 1-11\% of AET, calculated using the potential drainage data at TSD and PF, with NSE coefficients of 0.31-0.71 across the three sites. The \( K_{cFAO} \) and \( K_{cBright} \) time series led to over-estimates of \( AET_{pot} \) of 3-17\% and 29-55\%, respectively (Table 4.8).

Figure 4.19 Crop coefficient time series including: mean lysimeter site time series with AET calculated from measured drainage data (—) and estimated potential drainage (—); time series developed by Bright (2009a), converted to average monthly values (—); and time series range based on ‘initial’ and ‘mid’ stage \( K_c \) values given by Allen \textit{et al.} (1998) for a rotationally grazed pasture (——) (Section 2.4.1). ‘Initial’ stage value of 0.4 and a range of ‘mid’ stage values of 0.85 (lower line) and 1.05 (upper line) were applied where the pasture ground cover was <10\% and >95\%, respectively. Linear interpolation between the ‘initial’ and ‘mid’ stage values was used to estimate the ‘crop development’ stage values, according to the daily leaf area index values for the three sites.
Table 4.8  Summary statistics indicating crop coefficient time series performance in the prediction of actual evapotranspiration ($AET_{\text{obs}}$) from perennial ryegrass/white clover pastures at Larundel Dairy Farm, Three Springs Dairies and Pendo Farms for the period 07/09/2011-14/09/2012. NSE is the Nash-Sutcliffe efficiency and RMSD and NRMSD are the standard and normalised root mean square errors, calculated from data summed between subsequent soil moisture measurements. Values in brackets are the summary statistics indicating the performance of the time series when compared against $AET$ calculated with the estimated potential drainage data ($AET_{\text{pot}}$) from Figure 4.10 at TSD and PF.

<table>
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<th>Lysimeter site</th>
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<td>NRMSD</td>
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<td>NRMSD</td>
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4.3.5 Potential evapotranspiration estimation

Figure 4.20 compares the accumulated estimated potential evapotranspiration from each of the models tested with the measured AET, calculated using the observed drainage ($AET_{obs}$) at each of the three sites and estimated potential drainage ($AET_{pot}$) at TSD and PF (Figure 4.13). Table 4.9 provides a summary of the statistical comparison of the PET$_c$ estimates with $AET_{obs,pot}$. Graphs illustrating the relationship between daily $AET_{obs,pot}$ and PET$_c$ and the daily residuals (PET$_c$ – $AET_{obs,pot}$) for each PET$_c$ model tested are given in Appendices 18-24.

As illustrated in Figure 4.20 and summarised in Table 4.9, the methods tested yielded a range of predictions at the three sites. Each of the PM$_{FAO}$, PT and PM model predictions for TSD and PF were closer to $AET_{obs}$ than PET$_c$. This was due to the under-estimation of water losses by the lysimeters that were highlighted by the soil water flow modelling (Section 4.3.2.1), artificially increasing the $AET_{obs}$ calculations. The results of the drainage modelling suggested there should have been more drainage over the experimental period. However, this likely occurred as run-off from the lysimeters at TSD and PF, which was not quantified (Section 4.3.2.2). In contrast, the DMod, DCC and SWW models all yielded predictions closest to PET$_c$ at TSD and PF. At LDF, the DMod, DCC and SWW models provided closer predictions of PET$_c$ to $AET_{obs}$ compared with the PT, FAO and PM models due to the placement of rubber rims around the tops of the lysimeters preventing the surface redistribution of water. The remainder of the results detailed in this section will focus on the PET$_c$ predictions relative to PET$_c$ at TSD and PF, and $AET_{obs}$ at LDF.

The largest over-estimation of AET at each of the three sites was by the PM$_{FAO}$ method with over-estimations of 31-58%, followed by the PT (17-30%) and PM (8-29%) methods. Unsurprisingly, the NSE coefficients were lowest for the FAO-PET$_c$ predictions (<0-0.20), followed by the PT (<0-0.41) and the PM (<0.64) model predictions. The PT model tended to systematically over-estimate AET from approximately September/October through to April (Appendix 19). The FAO-PET$_c$ over-estimations persisted on a daily basis throughout the experiment, whereby the residuals (FAO-PET$_c$ – $AET_{obs}$) were consistently greater than zero (Appendix 20). This over-estimation provides further confidence that the predicted actual and potential soil moisture deficits at LDF, TSD and PF as illustrated in Figure 3.2, were too high, which was also reflected in the actual soil moisture measurements for the three sites (Figure 4.4). The time series of residuals for the PM model (Appendix 21) revealed a strong systematic error of under-estimation in the earlier stages of pasture growth and over-estimation during the latter stages, particularly at LDF and TSD. This indicated that there was at least one process not accounted for by the model. It was hypothesised that direct calculation of evaporation from the soil surface was the missing model process that was most likely to be the greatest contributor to the systematic error in the PM model. To test this, the DCC and SWW models, which separately calculate evaporation and transpiration in the process of estimating PET$_c$ were tested.
The DCC daily residual time series (DCC-PET\textsubscript{c} – AET\textsubscript{daily}) (Appendix 22) went some way towards reducing the systematic error identified in the PM model, although it was still present immediately following grazing. Optimising the DCC model parameters may further reduce this systematic error. However, given that the AET time series was based on measurements that have a \(~\)1 week time-step, at best, there wasn’t the temporal detail in the measured time series to justify parameter optimisation. When the DCC-PET\textsubscript{c} data were aggregated into time-steps that matched the time steps over which AET was estimated (Appendix 23), there was no obvious systematic error. The DCC model also yielded closer estimates of PET\textsubscript{c} to AET over the experimental period, being within 1-24%. However, estimations were improved by the SWW method, with differences of 1-9% over the experiment. The SWW model also achieved the highest NSE coefficients (0.27-0.76) and lowest NRMSD values (0.28-0.46) for the three sites. The systematic error of the residuals identified by the PM model, and to some degree still present with the DCC model, was absent (Appendix 24). DairyMod predicted PET\textsubscript{c} to within a similar degree of accuracy as the SWW model, with differences from AET over the experimental period of 6-14%, and NSE coefficients of 0.19-0.54. Daily SWW-PET\textsubscript{c} formed inputs into the HYDRUS model (Section 4.2.4.1). As the irrigation of the pasture prevented water stress, HYDRUS maintained the daily inputs of SWW-PET\textsubscript{c}.

Section 4.4.5 provides a detailed discussion of the model results.
Figure 4.20  Accumulated daily DairyMod (DMod-PET<sub>c</sub>), Priestley-Taylor (PT-PET<sub>c</sub>), FAO modified Penman-Monteith (FAO-PET<sub>c</sub>), Penman-Monteith (PM-PET<sub>c</sub>), dual crop coefficient (DCC-PET<sub>c</sub>) and Shuttleworth-Wallace (SWW-PET<sub>c</sub>) simulated potential evapotranspiration (---) and accumulated daily actual evapotranspiration (AET) (solid lines) from lysimeter-grown perennial ryegrass/white clover pastures at Larundel Dairy Farm (LDF), Three Springs Dairies (TSD) and Pendo farms (PF). Accumulated AET calculated with the measured drainage data is represented by — at LDF, — at TSD and — at PF, and AET calculated with the estimated potential drainage data is represented by — at TSD and — at PF, for the period 07/09/2011-14/09/2012.
Table 4.9 Summary statistics indicating model performance in the prediction of potential crop evapotranspiration (PET<sub>c</sub>), when compared with actual evapotranspiration (AET) measurements from perennial ryegrass/white clover pastures at Larundel Dairy Farm, Three Springs Dairies and Pendo Farms for the period 07/09/2011-09/09/2012. NSE is the Nash-Sutcliffe efficiency and RMSD and NRMSD are the standard and normalised root mean square errors, calculated from data summed between subsequent soil moisture measurements. Values in brackets are the summary statistics indicating the performance of the PET<sub>c</sub> models when compared against AET calculated with the estimated potential drainage data from Figure 4.10 at TSD and PF.

<table>
<thead>
<tr>
<th>Lysimeter site</th>
<th>Summary statistic</th>
<th>DairyMod</th>
<th>Priestley-Taylor</th>
<th>FAO Penman-Monteith</th>
<th>Penman-Monteith</th>
<th>Dual Crop Coefficient</th>
<th>Shuttleworth-Wallace</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total estimated PET&lt;sub&gt;c&lt;/sub&gt; (mm)</td>
<td>581</td>
<td>801</td>
<td>895</td>
<td>796</td>
<td>641</td>
<td>600</td>
</tr>
<tr>
<td>Larundel Dairy Farm</td>
<td>Variation from total AET (mm)</td>
<td>-34</td>
<td>187</td>
<td>281</td>
<td>181</td>
<td>26</td>
<td>-15</td>
</tr>
<tr>
<td></td>
<td>Variation from total AET (%)</td>
<td>-6</td>
<td>30</td>
<td>46</td>
<td>29</td>
<td>4</td>
<td>-2</td>
</tr>
<tr>
<td></td>
<td>Mean daily bias (mm/d)</td>
<td>-0.09</td>
<td>0.50</td>
<td>0.75</td>
<td>0.48</td>
<td>0.07</td>
<td>-0.04</td>
</tr>
<tr>
<td></td>
<td>NSE</td>
<td>0.19</td>
<td>-0.57</td>
<td>-0.44</td>
<td>-0.15</td>
<td>0.18</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>RMSD (mm)</td>
<td>0.97</td>
<td>1.34</td>
<td>1.29</td>
<td>1.15</td>
<td>0.97</td>
<td>0.92</td>
</tr>
<tr>
<td></td>
<td>NRMSD</td>
<td>0.48</td>
<td>0.67</td>
<td>0.64</td>
<td>0.57</td>
<td>0.48</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>Total estimated PET (mm)</td>
<td>512</td>
<td>721</td>
<td>878</td>
<td>701</td>
<td>689</td>
<td>551</td>
</tr>
<tr>
<td>Three Springs Dairies</td>
<td>Variation from total AET (mm)</td>
<td>-264 (-42)</td>
<td>-54 (167)</td>
<td>102 (323)</td>
<td>-74 (147)</td>
<td>-87 (134)</td>
<td>-225 (-3)</td>
</tr>
<tr>
<td></td>
<td>Variation from total AET (%)</td>
<td>-34 (-8)</td>
<td>-7 (30)</td>
<td>13 (58)</td>
<td>-10 (27)</td>
<td>-11 (24)</td>
<td>-29 (-1)</td>
</tr>
<tr>
<td></td>
<td>Mean daily bias (mm/d)</td>
<td>-0.71 (-0.11)</td>
<td>-0.15 (0.45)</td>
<td>0.27 (0.86)</td>
<td>-0.2 (0.39)</td>
<td>-0.23 (0.36)</td>
<td>-0.6 (-0.01)</td>
</tr>
<tr>
<td></td>
<td>NSE</td>
<td>-0.01 (0.54)</td>
<td>0.44 (0.41)</td>
<td>0.41 (0.09)</td>
<td>0.34 (0.64)</td>
<td>0.29 (0.43)</td>
<td>0.27 (0.76)</td>
</tr>
<tr>
<td></td>
<td>RMSD (mm)</td>
<td>1.46 (0.76)</td>
<td>1.08 (0.85)</td>
<td>1.12 (1.06)</td>
<td>1.17 (0.67)</td>
<td>1.22 (0.84)</td>
<td>1.24 (0.55)</td>
</tr>
<tr>
<td></td>
<td>NRMSD</td>
<td>0.57 (0.39)</td>
<td>0.42 (0.44)</td>
<td>0.44 (0.55)</td>
<td>0.46 (0.34)</td>
<td>0.48 (0.43)</td>
<td>0.49 (0.28)</td>
</tr>
<tr>
<td></td>
<td>Total estimated PET (mm)</td>
<td>606</td>
<td>821</td>
<td>921</td>
<td>760</td>
<td>712</td>
<td>639</td>
</tr>
<tr>
<td>Pendo Farms</td>
<td>Variation from total AET (mm)</td>
<td>-111 (-98)</td>
<td>104 (117)</td>
<td>204 (217)</td>
<td>43 (56)</td>
<td>-5 (8)</td>
<td>-78 (-66)</td>
</tr>
<tr>
<td></td>
<td>Variation from total AET (%)</td>
<td>-15 (-14)</td>
<td>15 (17)</td>
<td>28 (31)</td>
<td>6 (8)</td>
<td>-1 (1)</td>
<td>-11 (-9)</td>
</tr>
<tr>
<td></td>
<td>Mean daily bias (mm/d)</td>
<td>-0.3 (-0.26)</td>
<td>0.28 (0.31)</td>
<td>0.55 (0.58)</td>
<td>0.12 (0.15)</td>
<td>-0.01 (0.021)</td>
<td>-0.21 (-0.18)</td>
</tr>
<tr>
<td></td>
<td>NSE</td>
<td>0.42 (0.42)</td>
<td>0.29 (0.24)</td>
<td>0.25 (0.2)</td>
<td>0.42 (0.39)</td>
<td>0.38 (0.36)</td>
<td>0.48 (0.47)</td>
</tr>
<tr>
<td></td>
<td>RMSD (mm/d)</td>
<td>1.12 (1.12)</td>
<td>1.23 (1.28)</td>
<td>1.26 (1.32)</td>
<td>1.11 (1.15)</td>
<td>1.15 (1.18)</td>
<td>1.05 (1.07)</td>
</tr>
<tr>
<td></td>
<td>NRMSD</td>
<td>0.46 (0.48)</td>
<td>0.51 (0.54)</td>
<td>0.53 (0.56)</td>
<td>0.46 (0.49)</td>
<td>0.48 (0.5)</td>
<td>0.44 (0.45)</td>
</tr>
</tbody>
</table>
4.3.5.1 Comparison of Shuttleworth-Wallace modelled potential evapotranspiration using measured and modelled canopy data at Larundel Dairy Farm

Daily outputs of leaf area index and height from the DairyMod simulation at LDF (Section 3.3.8) were used as inputs to the SWW model to quantify differences in evapotranspiration estimations using simulated and observed pasture data (Table 4.10, Figure 4.21). This is important as often measured canopy data are not available. SWW-PETc estimated using modelled canopy data was <1% (4 mm) more annually than that estimated using measured canopy data, and 1.8% (11 mm) less than AET. When separated, the modelled canopy data led to annual soil evaporation predictions 28% (33 mm) more and transpiration predictions 6% (29 mm) less than the SWW-PETc calculated from measured pasture data, highlighting the importance of pasture LAI and height estimations on the evapotranspiration estimations (Section 4.4.5). Statistical comparison of the evapotranspiration estimations on a daily basis indicated that whether measured or modelled pasture growth data were used to estimate SWW-PETc, the results were comparable with an NSE coefficient of >0.99 and NRMSD of 0.02.

Table 4.10 Summary of total AET and Shuttleworth-Wallace (SWW) potential evaporation (E), transpiration (T), and evapotranspiration (PETc), calculated using observed and simulated pasture leaf area index (LAI) and height data for a perennial ryegrass/white clover pasture at Larundel Dairy Farm, Canterbury. Results are for the period 07/09/2011-14/09/2012. Values in brackets are the percentage differences from AET.

<table>
<thead>
<tr>
<th></th>
<th>E</th>
<th>T</th>
<th>Total AET, PETc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual evapotranspiration (AET)</td>
<td></td>
<td></td>
<td>615</td>
</tr>
<tr>
<td>SWW-PETc (observed pasture LAI and height)</td>
<td>120</td>
<td>480</td>
<td>600 (2%)</td>
</tr>
<tr>
<td>SWW-PETc (DairyMod-simulated pasture LAI and height)</td>
<td>153</td>
<td>451</td>
<td>604 (1%)</td>
</tr>
</tbody>
</table>
Figure 4.21  Accumulated Shuttleworth-Wallace (SWW) potential evapotranspiration (SWW-PETc) calculated using modelled (---) and measured (---) canopy leaf area and height data, and measured actual evapotranspiration (▲) (AET) (a) and SWW-PETc calculated using observed pasture data against SWW-PETc calculated using DairyMod-simulated pasture data (b), for perennial ryegrass/white clover pasture at Larundel Dairy Farm, Canterbury, for the periods 07/09/2011-14/09/2012. In (b) the solid line (―) shows the 1:1 relationship, the dotted line (---) is the fitted line. Form of the fitted line is $y = (0.98 \pm 0.001)x + 0.02 \pm 0.002$ ($r^2=0.99$).
4.4 Discussion

The aim of this chapter was to quantify actual evapotranspiration from irrigated, grazed dairy pasture across three commercial dairy farms in Canterbury, and evaluate the predictive abilities of a range of standard evapotranspiration models. In doing so, spatial variations in evapotranspiration across the Canterbury Plains have been quantified, and a ‘best approach’ method for estimating evapotranspiration from an irrigated dairy pasture has been determined. However, to achieve this, lysimeter drainage and changes in soil moisture needed to be quantified.

4.4.1 Soil water balance

Drainage, as a percentage of irrigation and rainfall inputs from the LDF and TSD lysimeters (39%) (Section 4.3.1.1) was within the typical range for Canterbury of 25-52% (Thorpe & Scott, 1999; White et al., 2003) (Section 2.3.3). For the PF lysimeters the percentage of water inflows that drained (11%) was lower and more representative of a dryland scenario where the majority of recharge occurs over winter months, with little or no recharge during the summer (Morgan et al., 2002). Coefficients of variation of the lysimeter drainage at each site ranged from 11% at LDF to 23% at TSD, which is within those reported for Canterbury soils in other studies (0.3-27%) (Section 2.3.3). The observed variation in drainage at each lysimeter site was therefore representative of the natural site heterogeneity. When the estimated potential drainage data were used in place of that measured at TSD and at PF (Figure 4.10), drainage as a percentage of irrigation and rainfall inputs at TSD increased to 64% and at PF to 14%.

The lower drainage at PF, both total and as a percentage of water inflows, was due to the heavier soils and smaller inputs of rainfall and irrigation. The soils at PF were deep with a total water holding capacity of ~239 mm (Table 3.10), no more than 5% sand content, and no stones (Appendix 3). Contrastingly, LDF and TSD had total water holding capacities of ~161 and ~189 mm (Tables 3.7 and 3.10), with much higher stone (up to 60%) and sand (up to 90%) contents (Appendices 1 and 2). At PF, this enabled more effective use of the applied rainfall and irrigation water. Additionally, when compared with atmospheric demand over the irrigation season (Table 3.5), the inputs of rainfall and irrigation were 215 mm (27%) less, and were therefore insufficient to maintain non-stressed conditions. This ultimately led to an increasing soil moisture deficit (Figure 4.4), with the potential consequence of pasture production losses. Mills et al. (2009) reported yield reductions for a cocksfoot pasture of 1.45%/mm when the soil moisture content fell below the critical deficit (Section 2.3.2.2). Minor pasture yield reductions of 3.4-7.5% were therefore likely based on soil moisture measurements of 1.2-4.0 mm below the critical level (Figure 4.4). This was estimated to equate to ~60 kg DM/ha over the experimental period, based on the simulated herbage growth rates (Figure 3.25), which in practice is negligible. However, as discussed in Section 2.3.2.2, pasture growth can become suboptimal prior to
the critical deficit being reached during extreme temperatures where the xylem cannot keep up with demand and the crop can become stressed even if the water supply is adequate (Kramer, 1983), although this was not able to be quantified in the current research. Despite this, the soil moisture deficits did allow for rainfall or irrigation inputs less than the moisture deficit to be held by the soil, which reduced the drainage.

Conversely, at LDF and TSD, total rainfall and irrigation inputs over the irrigation season were sufficient to maintain the soil moisture above the critical level, and for a majority of the time the soil moisture was held at or near field capacity (Figure 4.4). Up to 66 mm of the measured drainage at LDF and TSD, or 55 mm of the potential drainage at TSD was estimated to have occurred shortly following irrigation events (Section 4.3.1.1). If irrigation had been matched to the soil moisture deficit or held off to allow a deficit in the soil moisture of ~25-35 mm to be maintained prior to a rain event, this drainage could have been avoided. A deficit of ~25 mm would have left 10-30 mm of readily available water in the 700 mm soil profiles, preventing the risk of production losses. On average 33% and 46% of the drainage that occurred during the period of irrigation at LDF (159 mm) and TSD (57 mm) could have been avoided if greater soil moisture deficits had been allowed to develop. Therefore, in contrast to PF where large deficits of up to 67 mm occurred (Figure 4.4) and allowed for more effective storage of rainfall and irrigation, the LDF and TSD lysimeters were over-irrigated. Chapter 6 provides further analysis and discussion of over- versus deficit-irrigation.

4.4.2 Simulated soil water flow

4.4.2.1 Performance of HYDRUS and DairyMod in the simulation of lysimeter drainage

Both HYDRUS and DairyMod were used to simulate soil water flow at LDF, TSD and PF. Both models, as a whole, simulated profile drainage and soil moisture contents that followed the general trends of the observed data. However, HYDRUS was overall superior in its ability to model soil water flow. For example, at LDF, where rims were installed around the tops of the lysimeters preventing unquantifiable run-off losses, HYDRUS predicted drainage to within 27 mm (8%) of the observed compared with 40 mm (12%) by DairyMod. This was not surprising given the more dynamic and complex nature of HYDRUS (Section 2.3.3.4), which is dedicated to simulating soil water flow, unlike DairyMod which is a biophysical simulation model focused on dairy systems as a whole (Section 2.3.2.6). However, the results from DairyMod were still considered to provide a reasonable fit to the observed data. Both models over-predicted the observed drainage by 56% and 21% (HYDRUS) and 66% and 91% (DairyMod) at TSD and PF, respectively.

The high NSE coefficients achieved with HYDRUS (0.73-0.98) and DairyMod (0.62-0.85) provided confidence in the ability of both models to reasonably simulate drainage, although the NRMSD was high at 0.64-2.22 (Table 4.7). This was the result of a number of zero drainage days reducing the mean
of the observed drainage. Numerous studies have involved simulation of soil water flow with HYDRUS and validation of the model with measured data. For example, van der Velde et al. (2005) found HYDRUS to predict drainage to be within 9% of that measured, similar to the results at LDF (9%). Nothing could be found in the literature comparing actual drainage data with that simulated with DairyMod to relate to the results from this study. However, a number of studies have employed either DairyMod or EcoMod to predict drainage. Douglas et al. (2010), for example, coupled DairyMod with a surface irrigation hydraulic model, SRFR, to enable the simulation of the effects of border-strip irrigation scheduling and event management on irrigated pasture production systems. A scenario was tested comparing differing irrigation managements of ryegrass pasture on a clay loam soil, and model predictions of irrigation amounts, pasture growth and drainage were found to agree well with data reported in the literature for similar soils. Based on the results of the lysimeter experiment, it is considered that incorporation of HYDRUS into DairyMod would increase confidence in the model predictions. Cichota et al. (2008) used EcoMod, which has a common underlying biophysical structure to DairyMod (Johnson et al., 2008), to compare differences in simulated drainage when using observed or NIWA's virtual climate station data from several locations around New Zealand. While incorporation of HYDRUS into DairyMod may have improved the absolute drainage predictions, the study was focused on relative differences, and therefore the DairyMod predictions were likely sufficient for this purpose.

4.4.2.2 Potential for the surface redistribution of water

At LDF, the overall over-estimation of drainage by both DairyMod (40 mm) and HYDRUS (27 mm) when compared with the observed was relatively small, and within the error that would be expected. For example, drainage from the three lysimeters at LDF ranged from 332-402 mm, and therefore model deviations of 40 and 27 mm from the mean lysimeter drainage (357 mm) were approximately within the observed range. The installation of rubber rims around the top of the lysimeters at LDF (Section 4.2.1.1) prevented surface run-off of water from occurring, and therefore likely contributed to the close fit of the modelled drainage to the observed. This was supported at PF where rubber rims were found to improve the fit of the modelled drainage with that of the observed data based on a comparison of the drainage before and after the rims were installed (Figure 4.9). At TSD, however, no rubber rims were installed.

The results indicated that where there were no rims, water was being lost from the lysimeters through run-off processes, while surface redistribution of water onto the lysimeters from the surrounding pasture was restricted. This was due to a build-up of organic material at the lysimeter surface over time, as illustrated by Plate 4.4. This was coupled with the potential for edge flow (preferential flow of water between the steel casing and the soil) on the outside of the lysimeters, limiting the potential for redistribution of water onto, and drainage of water through, the lysimeters. The models translated the
loss of water due to run-off as drainage. Accordingly, differences in the modelled drainage with that observed at PF prior to the rim installation and at TSD were evident throughout the experiment.

Using the published infiltration rates for Templeton and Lismore soils (Section 2.3.3.2), and the measured rainfall and irrigation inputs at TSD and PF (Section 3.2.3.1), the potential for the run-off of water from the surface of the lysimeters was investigated.

Prior to the rubber rim installation around the top of the lysimeter casings at PF, ~67 mm of rain fell on the 19/10/2011 and 21/10/2011 at intensities of up to 10.8 mm/h, which had the potential to generate surface run-off (Section 2.3.3.2). The rain event triggered ~14 mm of drainage from the lysimeters, compared with 22 mm by HYDRUS and 39 mm by DairyMod. Accordingly, 8-25 mm of water may have run-off from the lysimeters. On a number of other occasions from mid-January to March, rainfall intensities at PF exceeded 10 mm/h and reached up to 23 mm/h. However, during these periods the soil moisture content of the soil was either near or below the critical level, and therefore infiltration into the soil may have been more rapid (Jiang, 2008) and drainage prevented due to the available storage capacity, as reflected by both the observed and simulated soil moisture data.

At TSD, there were a number of rainfall/irrigation events with intensities of up to 64.8 mm/h (Figure 3.3). As at PF, it is likely that while run-off may have occurred from the lysimeters, in the wider paddock this excess water would likely have translated as drainage due to surface redistribution. At the maximum intensity of 64.8 mm/h, for example, 10.8 mm of irrigation water was applied over a 10-minute period following 4 mm of irrigation over the previous 30 minutes on the 08/02/2012. This led to 9.1 mm of drainage simulated by HYDRUS and 8.4 mm simulated by DairyMod compared with the observed drainage of 2.3 mm, differences of 6.1-6.8 mm. Given the high intensity of the irrigation, run-off would likely have been triggered from the lysimeters. Over the 18-19/10/2011, rain fell at intensities of 1.2-3.6 mm/h for 24 hours, totalling 19 mm, wetting the soil to field capacity. This was followed by 9 hours of up to 9.6 mm/h, delivering a further 49 mm of rain. Overall 25.1 mm of drainage was observed compared with 52.2 and 47.0 mm simulated by HYDRUS and DairyMod. The difference again was likely due to run-off from the lysimeters. This supports the argument that re-distribution of water was likely at the lysimeter surface, and without the presence of rims around the tops of the lysimeters, run-off losses could not be quantified. However, both DairyMod and HYDRUS translated this loss of water as drainage, which is likely what would have occurred under standard field conditions or had rims been installed. Therefore, the modelled drainage could be confidently used in the water use calculations, for periods where rubber rims were absent.

4.4.2.3 Performance of HYDRUS and DairyMod in the simulation of soil moisture

When the modelled soil moisture was compared against the observed, the HYDRUS outputs provided a closer fit to the observed data at LDF and PF compared with DairyMod (Table 4.7). At TSD, both
HYDRUS and DairyMod predicted the soil moisture contents to a similar accuracy. NSE coefficients were, however, low at LDF and TSD, ranging from 0.17 to less than zero, which, as highlighted in the results, occurred due to the limitation of the NSE when coefficients of variation are small (ASCE, 1993). At PF the CV was higher (13%) and the NSE coefficient was 0.62 for HYDRUS but less than zero for DairyMod, respectively. Zhou et al. (2012) reported NSE coefficients of 0.74-0.87 when comparing the fit of HYDRUS soil moisture outputs to measure data, slightly higher than the 0.62 achieved at PF by HYDRUS. In the current research, the fit of the simulated and observed drainage was closer than the soil moisture.

Differences between each model and the observed data and between models can be explained. Differences between observed and modelled arose from the models’ inability to perfectly represent the complex nature of the soil-plant-water environment. This was compounded by the potential for errors in the measurement of SMC, including irregular timing counts of returning neutrons, equipment noise, random errors in the measurement of the time interval during which counts are accumulated for a single observation, and errors associated with spatial differences in soil moisture content and soil physical properties (Chanasyk & Naeth, 1996; Hewlett et al., 1964). There are also inherent errors with near surface measurements caused by the potential for neutron escape through the soil surface (Hillel, 1998; Jensen, 1983). For the lysimeter experiment, the calibrated near surface neutron probe measurements are considered to be the most likely error source. This was firstly due to the potential for neutron escape and secondly due to steep soil moisture gradients that can develop and rapid changes with time that likely occurred in the near-surface water content that can be difficult to account for. However, post-measurement corrections to the near-surface neutron probe measurements are considered to have provided sufficiently accurate measurements for the purposes of this study (Section 4.2.2.2).

Differences between models can be attributed to the different methods used by the models to solve for the volume of water in the soil at a particular time, as described in Sections 2.3.2.6 and 2.3.3.4. The concepts of field capacity and wilting point are central to tipping bucket style approaches, such as that used within DairyMod. However, according to de Jong and Bootsma (1996), these concepts are arbitrary and not intrinsic to the soil properties, and do not allow for the continuous redistribution of water through the profile according to the soil hydraulic characteristics. The result is the potential for lags to develop within the system, which were observed. For example, when DairyMod drainage predictions were compared on a daily then weekly basis at LDF, the NSE coefficient increased from 0.44 to 0.85 (Section 4.3.2.1). With HYDRUS, however, the difference was much smaller (0.03), reflective of the more dynamic response within the model to soil water flow. The use of the Richards equation (Equation 2.24) to simulate flow and the van Genuchten (1980) model (Equation 2.32) to describe the soil hydraulic characteristics of the profile within HYDRUS enable a more dynamic
response, whereby infiltration and redistribution of water through the profile are controlled by the physical factors governing water movement in soil (Section 2.3.3.4). At PF, however, the small decrease in the NSE coefficient (<0.1) when DairyMod drainage predictions were compared on a daily then weekly basis suggested there to have been minimal lag effect.

4.4.3 Pasture water use and water use efficiency

A benchmark WUE for a non-limited ryegrass/white clover pasture in Canterbury of 28 kg DM/ha/mm was established by Black and Murdoch (2013) (Section 2.3.2.4). The WUE of lysimeter-grown perennial ryegrass pastures at PF, LDF and TSD were 52-74% of the benchmark value at 14.5-20.6 kg DM/ha/mm, when measured drainage data were used in the AET calculations (Figure 4.15). The WUE was ~20 kg DM/ha/mm at TSD and PF when the estimated potential drainage was used.

The low WUE of the pastures was most likely a result of nitrogen deficiency. At the lysimeter sites, 13-23 kg N/ha was applied at the end of each grazing, totalling 173-230 kg N/ha/year (Section 3.2.4.4). These rates were lower than the 50 kg/N/ha and 75-100 kg N/ha required each grazing to achieve maximum WUE, as reported by Black and Murdoch (2013) and McKenzie et al. (2006), respectively. According to Mills et al. (2009), nitrogen is the main limiting factor to pasture growth, but this may not affect the total water use of the pasture. At PF for example, 689 mm of water (AET_{pol}) produced 14.9 t DM/ha while 542 mm of water at TSD and 615 mm of water at LDF produced 12.0 and 10.6 t DM/ha, respectively. However, with the same amount of water, using the 28 kg DM/ha/mm benchmark WUE for Canterbury, had the pastures been fully fertilised, total herbage yields could have increased to 15.2-19.3 t DM/ha. This was also identified in Section 3.4.1.3 for LDF with the application of an optimum TAGR. As discussed in Section 2.3.2.4, the canopy will control leaf growth according to nitrogen availability in order to maximise photosynthetic efficiency. Therefore, where the pasture is nitrogen-deficient, the transpiration potential prior to canopy closure will be reduced (Gastal & Durand, 2000; Grindlay, 1997; Johns & Lazenby, 1973). In contrast, the potential for soil water evaporation from the surface will increase, particularly under irrigation (Van Keulen et al., 1989), limiting the effect of N fertiliser on AET. Once full cover is achieved, the canopy will transpire at the potential rate (Mills et al., 2006), again diminishing the effects of N on AET. Therefore, where nitrogen is limiting, the total AET will be relatively unaffected. However, the total herbage production will be limited. The result is more water used per unit of pasture produced (Black & Murdoch, 2013; Mills et al., 2009) (Section 2.3.2.4).

In addition to under-fertilisation, nitrogen leaching losses caused by excess drainage may have contributed to the nitrogen deficiency (Section 4.3.1.1). Fraser et al. (1994) reported nitrogen from urine applications of 500 kg N/ha onto a Templeton silt loam soil growing perennial ryegrass in Canterbury to take 1-7 months to leach 1,200 mm through the soil. In total 8% of the applied nitrogen leached with 43% taken up by the plants. Given fertiliser applications at LDF, TSD and PF equated to
less than 50% of this, and fertiliser was only applied during the growing season when active uptake by the pasture would have occurred, it is likely that the pasture recovered the majority of the applied N, and N leaching is unlikely to have been significant. The clover content of the pasture at LDF was, however, low (Figure 3.14), possibly due to clover root weevil attack (Sections 3.2.4.1 and 3.4.1.4), and therefore reduced the potential for nitrogen fixation at that site. This potentially explains the lower WUE of 14.5 kg DM/ha/mm.

The elevated WUE of the pastures during spring 2011 was expected (Figure 4.16). Cooler temperatures during the spring allowed more available water to be used for growth rather than respiration, and remobilisation of the root reserves of nitrogen was likely. At TSD, mean daily temperatures in spring were 10°C, which increased to 14°C in summer. Similarly, at LDF and PF, mean daily temperatures increased from 11°C in spring to 15°C in summer. Tonmukayakul (2009) reported a higher WUE in spring (14.3 kg DM/mm) compared with summer (7.1 kg DM/mm) for ryegrass pastures in response to lower temperatures and lower vapour pressure deficits, although drought stress was also a contributing factor. Xiao et al. (2007) reported increases in the mean daily temperature of 1.7°C and 2°C led to WUE reductions of 7.3% and 12.5%, respectively.

At LDF, the initial spelling period of seven weeks following the first grazing of the season led to seed head development and remobilisation of underground reserves, which increased the dry matter content and subsequently the measured WUE to 40.7 kg DM/ha/mm, two times more than that of TSD and PF for the same period. According to Weinmann (1948), the underground components of perennial grasses (i.e., their roots) serve as a storage for carbohydrate reserves. The plants later use these reserves as a source of energy or as building material, for example, during flowering and seed formation. McCarty (1938) and McCarty and Price (1942) found underground carbohydrate stores of mountain brome (Bromus carinatus) and slender wheat grass (Agropyron trachycaulum) were lowest during active herbage growth and maximum when herbage growth had ended. Within the herbage, carbohydrates reduced during active growth but increased during flowering and seed development. Trethewey and Rolston (2009) reported increases of 107 and 160 mg DM/tiller in the internodes and seedhead of perennial ryegrass post anthesis in response to remobilisation of water soluble carbohydrates.

The reduction in the WUE from November to January coincided with the summer slump in pasture growth (Figure 3.25) when warm night temperatures, which averaged 11-12°C at the three sites, increased respiration rates relative to photosynthesis (Hay & Porter, 2006).

4.4.4 Crop coefficients

During the irrigation season months, monthly Kc values ranged from 0.56-1.11, when AET was calculated with measured drainage data, and from 0.56-0.87 when the estimated potential drainage
was used (Figure 4.17). Figure 4.19 compares an average of the three lysimeter sites’ time series from Figure 4.17 with those developed by Bright (2009a) for aperennial ryegrass pasture in Canterbury and Allen et al. (1998). From Figure 4.19, the site-averaged monthly $K_c$ time series values were largely within the range given by Allen et al. (1998), while the time series from Bright (2009a) was consistently higher, likely elevated due to surface run-off effects artificially increasing the apparent water use (Clothier et al., 2009).

The estimated $K_c$ values at the lysimeter sites were found to differ ($P<0.001$) spatially (i.e. between lysimeter sites) and temporally throughout the year. Accordingly, a single $K_c$ value or time series representative of all three sites was unable to be determined from the data. This is significant as within New Zealand a single $K_c=1$ is commonly assumed, or alternatively the values determined by Allen et al. (1998) or Bright (2009a) are used to estimate crop evapotranspiration. For example, Brown et al. (2010) used a $K_c=1$ for scheduling irrigation of pasture and $K_c$ values as given by Allen et al. (1998) for scheduling irrigation of wheat. A number of regional councils in New Zealand also assume a constant $K_c=1$ for estimating evapotranspiration. For example the Southland Regional Council applied a $K_c=1$ in their irrigation demand modelling of the Mataura catchment (Hughes et al., 2011). Similarly, the time series developed by Bright (2009a) was used for irrigation and drainage modelling of the Upper Waitaki Basin (Brown, 2008). However, the findings in the current research indicate that the application of $K_c$ values not derived from site-specific data is inappropriate for irrigation management purposes or when estimates of PET are required over shorter time periods, for example days.

While spatial and temporal differences in $K_c$ values, as observed at the three lysimeters sites, are not unique to the findings of this research, there is limited discussion throughout the literature of the causes of the differences. However, numerous attempts by others to either determine a single representative $K_c$ value or develop a common time series of $K_c$ values has highlighted difficulties (Fisher, 2012; Liu & Luo, 2010; Watanabe et al., 2004; Wright, 1982). Reasons are commonly attributed to crop growth and seasonal climatic variability and periods of water stress where irrigation (or precipitation) was insufficient. However, even when Fisher (2012) developed the time series based on growing-degree days to try and account for crop growth variability, the $K_c$ curve variability wasn’t reduced. Because of this, a mean $K_c$ time series is often adopted (Fisher, 2012; Jensen et al., 1990).

For the current study, the effects of climate, soil type, and on farm management of stock grazing and pasture fertility were all considered as possible reasons for the variation. Spatially, climate effects were considered negligible. This is because $K_c$ is a ratio of the measured actual water use to the potential reference crop water use; therefore, the effects caused by differences in climate are effectively removed. Furthermore, the coefficient of variation of the atmospheric demand among sites (4%) (Figure 3.2) was less than the variation in actual water use (~11%) (Figure 4.13) over the irrigation season. However, all sites were irrigated on a regular basis, and other than a short period during which
the soil moisture became limiting at PF, the soil moisture was maintained such that neither transpiration nor evaporation was restricted. Accordingly, given there was sufficient water available, the effects of soil type, N status of the pasture, and grazing frequencies and intensities were unlikely to impact AET. For example, where, due to limited N supplies, the leaf area of the pasture is smaller than an N sufficient pasture, or the pasture is grazed more frequently or to a smaller residual, also resulting in a smaller leaf area, the reduced transpiration that would result would be balanced by increases in evaporation from the exposed soil surface. The effects on AET, and therefore $K_c$, should be minor.

A reduction in variability among the sites, however, was achieved when daily estimates of water use, using the SWW method were used in the development of $K_c$ time series for each site. This was probably due to the smaller time step on which $K_c$ could be calculated with the modelled SWW data. If daily soil moisture measurements had been taken, it is expected that the differences among the sites would have been reduced. The temporal variability of the SWW-PET$_c$-derived $K_c$ time series appears to be seasonally driven. $K_c$ values increased during the summer months and reduced during the winter, which coincided with a fall in pasture growth rates to <5 kg DM/ha/d (Figure 3.12). Accordingly, while a single $K_c$ time series was statistically unable to be identified from the AET data, an average of the lysimeter site $K_c$ time series developed from AET data (with estimated potential drainage at TSD and PF) or the mean lysimeter SWW-PET$_c$-derived $K_c$ time series could be used to predict water use to within a reasonable accuracy over longer periods of time, for example over an irrigation season. The ability to apply either of the two time series to accurately estimate PET$_c$ at an independent site is examined in Chapter 5.

4.4.5 Potential crop evapotranspiration

Of the methods tested for estimating PET$_c$, the DairyMod and the Shuttleworth-Wallace model estimations provided the closest estimates to AET, when the estimated potential drainage was used at TSD and PF. The AET calculated using the measured drainage at PF, prior to the installation of rubber rims around the tops of the lysimeters (December 2011), and at TSD was considered to be artificially high due to the likelihood that run-off was occurring from the surface of the lysimeters, which was not quantified (Section 4.3.2). This unquantified water loss was assumed to be used by the plant in Equation 4.2, therefore increasing AET above what was likely. Accordingly, the remainder of this discussion relating to TSD and PF will address the performance of each of the tested models against AET calculated using the estimated potential drainage (AET$_{pde}$) in Figure 4.13b.

The PT, PM$_{FAO}$ and PM models all involve the sole prediction of potential evapotranspiration, without separation of the processes of evaporation and transpiration. Despite sufficient soil moisture availability, each of these models was found to over-predict AET at the three sites.
4.4.5.1 Priestley-Taylor

The simplicity of the PT model (Section 2.4.2.2) makes it an attractive alternative to each of the other models tested, and is therefore often applied (Clothier et al., 1982; Green et al., 1984). However, underlying assumptions of the model limit its representativeness of a grazed pasture and led to over-predictions of AET of 17-30% (117-187 mm) over the experimental period (Table 4.9). While the model does not include any direct canopy variables, the constant empirical coefficient ‘α’ represents the convection of dry air across the pasture, and assumes canopy closure and a wet surface (Section 2.4.2.2). Accordingly, the variability in the canopy height, leaf area, and ground coverage under a grazing operation is not accounted for by the PT model, particularly during the growing season when the pasture at all three sites was frequently defoliated due to grazing, and therefore was unsuitable for estimating water use under the conditions of this research. The potential to improve PT-PET estimates and reduce the seasonal systematic over-estimation through optimisation of the coefficient α was investigated. Optimisation involved adjustment of α from the default 1.26 by either maximising the NSE coefficient or reducing the difference between the PT-PET estimates and AET (or AET_{pot} at TSD and PF) to zero, for which the Excel ‘solver’ function was used. Maximising the NSE resulted in values of α of 0.85-0.98 for the three sites, and NSE coefficients increased to 0.30-0.76. Accumulated differences between PT-PET and AET were 1-74 mm (<1-12%). Optimising α to reduce the differences to zero resulted in values of α of 0.97-1.08 for the three sites, and NSE coefficients of 0.23-0.76. These results suggest that α should have a value of ~0.97 when the PT is used to estimate PET for an irrigated, grazed pasture. However, despite the improvements, other models tested (i.e. DairyMod, SWW, DCC) yielded closer fits to the observed data.

Jamieson (1982) suggested that PT model estimates can also be affected by increases in the slope of the saturation vapour pressure-temperature curve if transpiration is reduced in response to stomatal closure. This can lead to increases in the vapour pressure deficit and temperature due to the manifestation of energy not used in evapotranspiration as heat. This is possible in Canterbury where strong north west winds and high temperatures can frequently occur, leading to stress within the canopy despite sufficient water availability (Jamieson, 1982; Kramer, 1983; Scotter & Heng, 2003) (Section 2.3.2.2). However, the effects of this on the PT model are less than those for the PM model, which includes a vapour deficit term (Jamieson, 1982). In the current lysimeter study, while this may have had an effect on the PT estimations, it appears that the value of α was the dominant contributor to the systematic seasonal over-estimation.

4.4.5.2 FAO modified Penman-Monteith

The PM_{FAO} model, with which PET_{o} is estimated for a theoretical reference crop (i.e. actively-growing, full coverage, uniform height of 0.12 m) using standard climate data, is another model often used to estimate crop evapotranspiration (Scotter & Heng, 2003). However, in the current experiment, the
over-estimation was even greater than that by PT, at 31-58% (differences of 217-323 mm) of the total AET (Table 4.9). As with PT, PM$_{FAO}$ does not require inputs of canopy leaf area and height so takes no account of the actual canopy, but is controlled solely by climatic variables. Thus the model’s relative simplicity, plus the option of easily estimating climate data where they are missing (Allen et al., 1998; Trajkovic & Kolakovic, 2009), makes it an attractive option. Accordingly, the PM$_{FAO}$ model evapotranspiration estimations represent the maximum potential, for a pasture with no limitations, in proportion to climatic demand. Again, this is not representative of a dairy pasture subject to regular grazing, and as observed at LDF, nitrogen deficiency, which leads to a reduced leaf area and therefore reduced ground cover (Section 3.4.1.7).

4.4.5.3 Penman-Monteith

The PM model over-estimated the lysimeter AET by 15-29% over the experiment (Table 4.9), which is similar to the 8-29% difference reported by Clothier et al. (1982) (Section 2.4.3), and an improvement on the evapotranspiration estimations by PT and PM$_{FAO}$. At all three sites the PM-PET$_c$ over-estimations included both under- and over-predictions depending on the stage of pasture regrowth (Appendix 21). This was attributed to the PM methodology, which includes inherent assumptions (Section 2.4.2.1) that the pasture completely shades the ground, is green, well-watered, actively-growing, and of uniform height. Typical grazed dairy pasture in Canterbury, for example, will often not meet these specifications. At LDF for example, full cover, represented by 95% PAR interception, was achieved at an LAI of ~4 (Figure 3.17). However, as illustrated by Figure 3.20, the LAI of the pasture was at or above this only 12% of the time. At TSD and PF the LAI of the pastures ranged from 0.9-2.9 and 0.9-4.2, respectively (Figure 3.26), and therefore did not, or rarely reached the LAI=4 found to be representative of full cover at LDF. Accordingly, the PM was not able to sufficiently represent the grazed pastures in the lysimeter experiment.

Measured (LDF) and modelled (TSD and PF) canopy height and LAI of the pasture were used in the estimation of daily $r_s$ and $r_c$ values. However, uncertainties existed in relation to turbulent transport, stomatal control, and the ‘active’ leaf area fraction, which is a common criticism of the PM model (Section 2.4.2.1). At LDF, for example, the pasture was generally defoliated to a height of ~60 mm (Figure 3.16) and LAI of ~0.6 (Figure 3.20). At its maximum it increased to more than 350 mm in height with an LAI >5. Accordingly, the assumption that the upper half of the canopy is actively contributing to leaf heat and vapour exchange, which is based on a constant pasture height of 120 mm and LAI of ~2.9 (Allen et al., 1998), is not representative of a grazed pasture. When the pasture was shorter with a lower LAI, a much larger proportion was likely to be actively contributing, reducing the crop resistance and increasing the measured evapotranspiration. Conversely, when the pasture was longer and the LAI greater than 2.9, a smaller proportion may have been contributing, increasing the crop resistance and reducing the measured evapotranspiration below that predicted. Furthermore, rapid
changes in the pasture cover due to stock grazing, which alter the relative evaporation and transpiration contributions of evapotranspiration, are not accounted for in the PM model, and therefore its use during these early growth stages may be inappropriate (ASCE, 1996; Ershadi et al., 2015).

4.4.5.4 Dual crop coefficient and Shuttleworth-Wallace

When the evaporation and transpiration components were separated using the DCC and SWW models, the residuals were reduced and cumulative error largely eliminated. PET_c predictions were also closer to AET, with total differences of <1-24% (DCC) and <1-9% (SWW). Unlike the PM and PT models, the multi-layered DCC approach accounted for the combined variation in soil water evaporation and canopy transpiration that occurs under a grazed system. This was achieved through incorporation of the canopy variables of height and LAI, and by accounting for changes in ground cover, and therefore soil exposure and the potential for soil surface evaporation. This, coupled with a daily water balance of the soil surface enabled more accurate prediction of the daily soil water evaporation component, and the canopy transpiration potential. The predictions with the SWW model were, however, superior to those with the DCC model, a result of more complexity regarding the canopy demand. While both models have, to some degree, been developed from the PM model, the SWW model is more physically based, working from the ground up to calculate evaporation and transpiration simultaneously (Section 2.4.2.4). The DCC approach starts with a possible maximum PET_c determined by the energy available for evapotranspiration at the soil surface, following rainfall or irrigation (Section 2.4.2.3). The potential transpiration is estimated according to crop stage and standard transpiration coefficients for pasture, and then the evaporation is set equal to the balance of the maximum PET_c minus the potential transpiration, once any surface water limitations are accounted for. A downfall of both models, which is also present in each of the PT, PM and PM_{FAO} models is that the models assume non-limiting water conditions for transpiration. At each of the three lysimeter sites, this limitation was not particularly evident due to irrigation maintaining sufficient moisture availability throughout the experiments, except for at PF where short periods of water stress occurred, although they were relatively brief and unlikely to have made a significant impact on the overall water use.

4.4.5.5 DairyMod

The DairyMod model provided similar predictions of soil PET_c to the SWW model, and therefore where leaf area and height are unknown, DairyMod could be used directly to estimate water use to within a reasonable accuracy. The method used within the DairyMod model for estimating PET_c is similar to that employed within the SWW model in its account for the canopy, although it has added dynamism surrounding the soil-plant-water interactions more easily incorporated into a computer simulation model (Section 2.3.2.6). This is particularly in regards to the ability of the model to account for effects of soil water availability to the plant. The DairyMod model estimates a maximum potential
transpiration rate according to the PM model. From the maximum, DairyMod determines the actual transpiration component in proportion to the ground cover, which is then adjusted according to the soil water status of the profile using an approach similar to Feddes water uptake reduction model (Feddes et al., 2001; Feddes et al., 1978). The maximum potential evaporation rate of water from the soil is estimated from a modified form of the PM equation, whereby the resistance to water movement through the leaf stomata is removed. The actual evaporation rate is then defined by the model according to the soil water availability and depth of water in the soil profile, where the potential to evaporate from the soil declines with depth.

4.4.5.6 General
The results of the PETc modelling highlight the importance of factoring variations in the canopy into predictions of water use. Separation of evapotranspiration into soil water evaporation and canopy transpiration is also essential, particularly in a grazed system, for predictions to be made accurately and then used with confidence.

The importance of having accurate measurements or estimations of canopy leaf area and height were also identified by the modelling, where the effects of using measured and modelled canopy LAI and height in the SWW model were compared. The overall predictions of PETc were comparable, with a difference of 4 mm over the experimental period, which in practice is negligible. However, differences were apparent between the evaporation and transpiration components of the total evapotranspiration predictions (Table 4.10). This highlights that, under irrigated conditions where the surface soil water is not limiting evaporation, to attain accurate estimations of PETc, precise estimates of height and LAI may not be necessary. However, for obtaining a holistic picture of water use, accurate LAI and height is necessary. For example, at LDF, when measured canopy data were used the estimated evaporation and transpiration components were 120 and 480 mm, respectively, compared with 153 and 451 mm when the DairyMod-simulated pasture data were used. These differences have implications for water management decisions, whereby water use can potentially be reduced through the reduction of evaporation losses through varying irrigation practices. For example, applying more irrigation water less frequently would prevent constant wetting of the surface, and therefore may reduce the total time the surface of the soil is subject to evaporative losses over the season (Mermoud et al., 2005). This is explored further in Chapter 6.
4.5 Conclusions

The results in this chapter demonstrate that AET varies spatially across the Canterbury Plains and that it could not be modelled accurately by using the same crop coefficient time series at all sites, thus proving the hypothesis to be true. The results also demonstrate that AET can be modelled to within a reasonable accuracy using the SWW PET$_c$ model, providing measured or modelled pasture canopy data specific to each site are available. This highlights the importance of accounting for variations in the canopy through separation of the processes of soil surface evaporation and canopy transpiration in the estimation of the potential evapotranspiration. Accordingly, of the models tested, the DCC and SWW provided the most accurate estimates of PET$_c$ to AET. The results therefore suggest that the SWW method should be used in favour of the current ‘best practice’ PM model when estimating evapotranspiration from an irrigated, grazed dairy pasture in Canterbury. Further to this, the following conclusions can also be drawn from the results of Chapter 4.

Objective four was achieved in this chapter through the quantification of lysimeter drainage and soil moisture, and ultimately the calculation of AET for each lysimeter site. Drainage, as a percentage of inflows and drainage variability among lysimeters at each site was typical of Canterbury conditions. However, up to 55 mm and 66 mm of the drainage at TSD and LDF, respectively, could have been avoided with improved irrigation management. Consequently, total water use could have been reduced by up to 11% at LDF and 10% at TSD. While both TSD and LDF were over-irrigated leading to excess drainage, at PF soil moisture deficits during the growing season resulted in minimal drainage losses.

Soil water flow simulations using DairyMod and HYDRUS highlighted the potential for run-off from the surface of the lysimeters. This occurred where rubber rims were not installed to prevent surface redistribution of water, and therefore ensure all water inputs and outputs were able to be quantified. Accordingly, at PF, prior to the installation of rubber rims in December 2011 and at TSD where no rims were installed, the calculated AET was found to be higher than would likely occur under standard field conditions. When the HYDRUS-modelled drainage was used in place of the measured for periods where there were no rims, AET predictions became more realistic and in line with those predicted by DairyMod and the DCC and SWW models.

Differences between the DairyMod and HYDRUS predictions of drainage and soil moisture were small, but overall HYDRUS was superior. This was a result of the dedicated focus of HYDRUS to simulating soil water flow, enabling a greater degree of complexity and dynamism compared with DairyMod, which has been designed as a biophysical model for dairy systems.

Objective 6 involved the development and assessment of crop coefficient time series for estimating evapotranspiration, and evaluation of standard PET$_c$ models’ ability to accurately predict
evapotranspiration for irrigated, grazed dairy pastures. Spatial variations in the derived $K_c$ time series were attributable to the time step over which $K_c$ was estimated (i.e. weekly-two weekly time steps), while temporal variations were seasonally driven. Statistical analysis of $K_c$ time series for the lysimeter sites indicated that no single representative time series could be developed from the data due to differences among sites. However, when monthly averaged $K_c$ time series were developed from daily, rather than weekly-two weekly data, differences among the sites were reduced. When a mean of the lysimeter site time series was used to estimate PET$_c$ at each of the three sites, predictions of evapotranspiration over the irrigation season were comparable in accuracy to those achieved with either the SWW PET$_c$ model or DairyMod. Use of the time series developed from standard values given by Allen et al. (1998) also yielded predictions to within a similar accuracy. Other $K_c$ time series used in the prediction of irrigated pasture water use in Canterbury, including the time series developed by Bright (2009a) and the use of a single value of $K_c=1$ (equal to the PM$_{FAO}$ model predictions), over predicted seasonal water use by 32-56% and 34-60%, respectively. Overall, while the spatial variability in evapotranspiration between the sites precluded the use of a single $K_c$ time series for irrigation management, the lysimeter site-averaged time series could be used for water allocation management purposes, for which estimates over longer time steps are acceptable. Yet, the results support the use of the SWW model for irrigation management purposes, for which PET$_c$ estimates over shorter time steps could be achieved, where site-specific measured or modelled pasture canopy data are available.

The importance of vegetation in controlling evapotranspiration was highlighted throughout the results. The plant is not a simple passive interface between the climate and the soil; rather it is a dominant component that incorporates the effects of climate and soil. Neither the PT nor the PM$_{FAO}$ models actively accounted for the canopy in their estimations of PET. The PM model provided for the interactions between the plant and atmosphere. However, it was unable to sufficiently account for the complexities associated with varying vegetation height or canopies with low LAI, as occurs under a pastoral grazing system. This stems from the inherent assumptions in the model of a closed, uniform, well-watered, actively-growing crop. This was largely overcome through use of the DCC and SWW models where soil evaporation was separated from transpiration and then recoupled. Doing so reduced the degree of error and the systematic pattern to the error in the estimation of irrigated dairy pasture water use. This highlighted the importance of the plant characteristics, and that the method of estimation used needs to account for the separate influencing processes of soil evaporation and canopy transpiration.

Finally, the accuracy of the pasture height and LAI data in PET$_c$ estimations was found to be important for obtaining an overall understanding of the water use of the pasture. However, within an irrigated system the accuracy of the LAI and height data had little bearing on the overall predictions of PET$_c$ due to a balancing of transpiration reductions by increases in soil surface evaporation, and vice versa.
Chapter 5
Validation of Pasture Growth, Soil Water Flow and Potential Evapotranspiration Estimation Models at Iversen Field, Lincoln, Canterbury, Under Varying Pasture Performance

5.1 Introduction

Chapters 3 and 4 tested the hypothesis that the variability in evapotranspiration from irrigated pasture across the Canterbury Plains limits the use of a single crop coefficient time series at all locations for accurately modelling evapotranspiration from pasture for the purpose of irrigation management. However, the SWW model was proved to provide an effective method, with which accurate estimations of AET could be achieved over shorter time steps; the influences of the canopy need to be actively accounted for. In Chapter 3, pasture growth was quantified for the three lysimeter sites through a combination of on-site measurements and simulations of growth using the biophysical model DairyMod, which was calibrated against observed lysimeter-grown ryegrass herbage accumulation. In Chapter 4, the spatial variability of AET across the three lysimeter sites was quantified, which necessitated the simulation of drainage. Both DairyMod and HYDRUS were found to be comparable in their predictions of drainage. However, HYDRUS was overall found to be superior based on the accuracy of the simulated data. Pasture growth data from Chapter 3 were used to assess the predictive ability of a number of potential evapotranspiration models, which identified that the SWW model achieved predictions closest to AET.

Validation of DairyMod and HYDRUS in their prediction of pasture growth and/or soil water flow, and DairyMod, SWW and the lysimeter site averaged Kc time series in their prediction of PETc is required to gain confidence in their broader applicability. The objective of Chapter 5 is therefore to validate the HYDRUS, DairyMod, SWW and Kc models with an independent data set (Objective 4). For this, a previously published data set was used. These data were collected as part of a research project investigating how nitrogen fertiliser and irrigation affected the water use efficiency of a perennial ryegrass/white clover pasture at Lincoln University (Black & Murdoch, 2013). The range of yields generated is expected to cover those produced on irrigated dairy farms in Canterbury.

5.2 Methods and Materials

5.2.1 Site

The experimental site was flat, located within Iversen Field (block I8) of the Field Research Centre at Lincoln University, Canterbury, New Zealand (NZGD 2000 43° 38.9'S, 172° 28.1E, 11 m a.s.l.).
5.2.2 Soil

The soil at the experimental site is a deep (>2 m) Wakanui silt loam (Udic Ustochrept, USDA Soil Taxonomy) (Brown et al., 2005) derived from greywacke alluvium, and is one of the major soil series of the Canterbury Plains (Cox, 1978; U.S.D.A., 1984; Webb et al., 2000). Wakanui soils are characterised as being imperfectly drained, leading to distinct yellow-brown mottles below ~0.26 m and strong mottling below 0.7 m. Wakanui topsoils generally consist of uniform silt loams ranging in depth from 0.18-0.35 m, although are typically 0.20-0.25 m deep. Subsoils vary in texture from silt and clay loams down to a depth of ~0.70 m followed by sand and silt loams (Cox, 1978; Watt & Burgham, 1992).

The volumetric soil moisture content of the soil at the experimental site has been identified as being ~35% at field capacity, critically limiting to the canopy at 24%, and ranging from 8-20% at the permanent wilting point (Black & Murdoch, 2013; Brown, 2004; Webb et al., 2000). The saturated hydraulic conductivity of this soil has been reported to range from >1,700 mm/d through the coarser textured layers to <10 mm/d in the finer layers (Greenwood, 1989; Watt & Burgham, 1992; Webb et al., 2000). Soil water retention and saturated hydraulic conductivity measurements for a Wakanui silt loam taken within 1.4 km of the experimental site are provided in Table 5.1.

The results of a soil test carried out in January 2011 identified the soil fertility to be moderate, with no maintenance fertiliser applied (Table 5.2).
Table 5.1  Soil water content (%) at varying matric potentials and saturated hydraulic conductivity values for a Wakanui silt loam soil, Lincoln, Canterbury.

<table>
<thead>
<tr>
<th>Soil depth (mm)</th>
<th>Matric potential (kPa)(^1)</th>
<th>(-1)</th>
<th>(-2)</th>
<th>(-3)</th>
<th>(-5)</th>
<th>(-10)</th>
<th>(-30)</th>
<th>(-100)</th>
<th>(-300)</th>
<th>(-1500)</th>
<th>(K_{sat}) (mm/d)(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-50</td>
<td></td>
<td>39</td>
<td>38</td>
<td>36</td>
<td>34</td>
<td>33</td>
<td>30</td>
<td>28</td>
<td>25</td>
<td>20</td>
<td>1608</td>
</tr>
<tr>
<td>50-100</td>
<td></td>
<td>44</td>
<td>42</td>
<td>41</td>
<td>38</td>
<td>35</td>
<td>33</td>
<td>30</td>
<td>27</td>
<td>20</td>
<td>1608</td>
</tr>
<tr>
<td>100-150</td>
<td></td>
<td>44</td>
<td>42</td>
<td>40</td>
<td>37</td>
<td>35</td>
<td>33</td>
<td>30</td>
<td>27</td>
<td>20</td>
<td>1608</td>
</tr>
<tr>
<td>150-200</td>
<td></td>
<td>43</td>
<td>42</td>
<td>40</td>
<td>37</td>
<td>35</td>
<td>33</td>
<td>29</td>
<td>27</td>
<td>20</td>
<td>1608</td>
</tr>
<tr>
<td>200-250</td>
<td></td>
<td>39</td>
<td>38</td>
<td>36</td>
<td>35</td>
<td>33</td>
<td>31</td>
<td>28</td>
<td>23</td>
<td>16</td>
<td>720</td>
</tr>
<tr>
<td>250-300</td>
<td></td>
<td>38</td>
<td>37</td>
<td>35</td>
<td>34</td>
<td>32</td>
<td>30</td>
<td>27</td>
<td>23</td>
<td>16</td>
<td>720</td>
</tr>
<tr>
<td>300-350</td>
<td></td>
<td>35</td>
<td>34</td>
<td>33</td>
<td>32</td>
<td>30</td>
<td>29</td>
<td>27</td>
<td>23</td>
<td>17</td>
<td>720</td>
</tr>
<tr>
<td>350-400</td>
<td></td>
<td>34</td>
<td>33</td>
<td>32</td>
<td>31</td>
<td>29</td>
<td>28</td>
<td>27</td>
<td>24</td>
<td>17</td>
<td>36</td>
</tr>
<tr>
<td>400-450</td>
<td></td>
<td>32</td>
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<td>31</td>
<td>30</td>
<td>29</td>
<td>28</td>
<td>27</td>
<td>24</td>
<td>17</td>
<td>36</td>
</tr>
<tr>
<td>450-500</td>
<td></td>
<td>34</td>
<td>33</td>
<td>33</td>
<td>32</td>
<td>31</td>
<td>30</td>
<td>28</td>
<td>25</td>
<td>18</td>
<td>36</td>
</tr>
<tr>
<td>500-550</td>
<td></td>
<td>35</td>
<td>34</td>
<td>34</td>
<td>33</td>
<td>32</td>
<td>31</td>
<td>29</td>
<td>25</td>
<td>17</td>
<td>48</td>
</tr>
<tr>
<td>550-600</td>
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<td>35</td>
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<td>31</td>
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<td>24</td>
<td>18</td>
<td>48</td>
</tr>
<tr>
<td>600-650</td>
<td></td>
<td>36</td>
<td>35</td>
<td>35</td>
<td>34</td>
<td>33</td>
<td>31</td>
<td>28</td>
<td>23</td>
<td>18</td>
<td>48</td>
</tr>
<tr>
<td>650-700</td>
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<td>36</td>
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<td>35</td>
<td>34</td>
<td>33</td>
<td>32</td>
<td>29</td>
<td>24</td>
<td>18</td>
<td>48</td>
</tr>
</tbody>
</table>

Note 1: Data are means of five replicates sourced from Greenwood (1989) based on measurements conducted 1.4 km east of the experimental site.

Note 2: Data from Watt and Burgham (1992) based on measurements conducted 1.4 km north of the experimental site.

Table 5.2  Soil test results (0-75mm) in January 2011 for Iversen Field block I8 at Lincoln University, Canterbury.

<table>
<thead>
<tr>
<th>Date</th>
<th>pH (H(_2)O)</th>
<th>Olsen P (mg/L)</th>
<th>SO(_4)-S (mg/kg)</th>
<th>Ca(^{2+}) (me/100g)</th>
<th>Mg(^{2+}) (me/100g)</th>
<th>K(^+) (me/100g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January 2011</td>
<td>5.9</td>
<td>22</td>
<td>3</td>
<td>7.1</td>
<td>1.02</td>
<td>0.9</td>
</tr>
<tr>
<td>Normal range levels</td>
<td>5.7-6.2</td>
<td>20-30</td>
<td>10-20</td>
<td>4-12</td>
<td>0.6-1.6</td>
<td>0.3-0.6</td>
</tr>
</tbody>
</table>

Note: Soil samples were analysed using Ministry of Agriculture and Fisheries Quick Test MAF procedures. The normal range levels were taken from the Hill Laboratories Crop Guides for ryegrass and mixed pasture (Hill Laboratories, 2015)

5.2.3 Climate

Climate data were sourced from the nearby Broadfields meteorological station, located 3 km north of the experimental site. Data from the Lincoln meteorological station were used to determine the long-term means (LTM).

5.2.3.1 Rainfall, evapotranspiration and irrigation

Annual rainfall over the two-year experimental period (06/08/2011-31/07/2013) varied. The first year (2011/12) had a total annual rainfall of 607 mm (06/08/2011-06/08/2012), 5% less than the LTM of 640 mm (Table 5.3). In the second year (2012/13), the annual rainfall totalled 787 mm (07/08/2012-
31/07/2013), 23% greater than the LTM. However, despite being drier annually, rainfall during the irrigation season (1 September-30 April) of 2011/12 (410 mm) exceeded the LTM of 389 mm by 5%. In 2012/13, the irrigation season rainfall (335 mm) fell short of the LTM by 14%. Accordingly, less irrigation water was applied during the 2011/12 irrigation season (125 mm) compared with the 200 mm in the second year. In total, 535 mm of rainfall and irrigation were applied in each of the 2011/12 and 2012/13 irrigation seasons.

Daily maximum rainfall and irrigation intensities, calculated from the 10-minute Broadfields meteorological station data (rainfall) and on-site irrigation measurements, ranged from a minimum of 1.2 mm/h up to maximum of 51.6 mm/h, and were generally highest during the period of irrigation each year (Figure 5.1).

Annual PET\(_o\) totalled 868 mm in 2011/12, lower than the long-term annual average of 906 mm. In 2012/13 PET\(_o\) was similar to the LTM at 929 mm.

Figure 5.2 provides a soil water budget over the two-year experimental period, showing the daily PET\(_o\), rainfall, irrigation and actual and potential soil moisture contents. The potential soil moisture deficits with and without irrigation applied were estimated with Equation 3.2 using the daily PET\(_o\) and rainfall and irrigation data, with a starting soil moisture deficit of 10 mm for each year on 06/08/2011 and 06/08/2012, based on on-site soil moisture measurements (Figure 5.13).

For the 500 mm soil profiles, the estimated PSMD without irrigation reached maximums of 434 and 572 mm in 2011/12 and 2012/13, respectively. With irrigation, the PSMD was maximal at 309 mm in 2011/12 and 372 mm in 2012/13. These data suggest that soil moisture may have been a limiting factor to pasture growth for both the irrigated and dryland treatments. However, the calculated deficits are in excess of the total water holding capacity of the 500 mm soil profile. This may indicate that the pasture is abstracting water from below a depth of 500 mm. Also, as identified in Chapter 4, the estimation of evapotranspiration demand from climate data only (i.e. FAO-PET\(_o\)), is likely to overestimate the actual crop demand (Section 4.3.5), and therefore the actual soil moisture deficit was likely less than that estimated in Figure 5.2.
Table 5.3  Rainfall, irrigation and reference crop potential evapotranspiration ($\text{PET}_o$) for Iversen Field (I8) at Lincoln University. Values presented are the annual and irrigation season values for the long-term mean (LTM) and for the two-year experimental period. Irrigation season (months September-April) values are in brackets.

<table>
<thead>
<tr>
<th>Experimental period</th>
<th>Rainfall (mm)</th>
<th>Irrigation (mm)</th>
<th>PET$_o$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011/12</td>
<td>607 (410)</td>
<td>(125)</td>
<td>868 (743)</td>
</tr>
<tr>
<td>2012/13</td>
<td>787 (335)</td>
<td>(200)</td>
<td>929 (811)</td>
</tr>
<tr>
<td>LTM</td>
<td>640 (389)</td>
<td></td>
<td>905 (774)</td>
</tr>
</tbody>
</table>

Note 1: Experimental periods 2011/12 and 2012/13 extend from 06/08/2011-06/08/2012 and 07/08/2012-31/07/2013, respectively.

Note 2: LTM rainfall values were sourced from NIWA’s Lincoln and Broadfields meteorological stations (3 km north of the experimental site) for the period 1972-2013.

Note 3: LTM PET$_o$ was calculated with Equation 2.42 using solar radiation, air temperature, relative humidity and wind speed data from NIWA’s Broadfields meteorological station for the period 1999-2013.

Figure 5.1  Stacked daily maximum rainfall (■) and irrigation (■) intensities (mm/h) recorded at the Broadfields meteorological station (rainfall) and at Iversen Field (I8), Lincoln University (irrigation) from 06/08/2011 to 31/07/2013. Rainfall intensities are calculated from 10-minute data.
5.2.3.2 Air temperature and solar radiation

Monthly averaged mean daily air temperature and solar radiation followed similar patterns over the two-year experimental period (Figure 5.3). Mean daily air temperature peaked at 15-17°C in January of each year, and fell to 6-7°C in June. Monthly averaged mean daily total solar radiation increased from a minimum of 4-5 MJ/m²/d in June to a maximum of 23-26 MJ/m²/d through November-January of each year.
Mean daily air temperature (■) and mean daily solar radiation (◆), by month, for August 2011 to July 2013. Data were sourced from the Broadfields meteorological station, Lincoln, Canterbury.

5.2.3.3 Relative humidity and wind speed

Monthly averaged mean daily relative humidity varied throughout the two years (Figure 5.4), although was generally highest from April-August, reaching a maximum of 89% in June 2013. The lowest recorded mean daily value was 69% for January 2013. Mean daily wind speed followed a similar pattern in each season with maximum values of 4-5 m/s from September-March, falling to <4 m/s from April-August (Figure 5.4).

Mean daily relative humidity (■) and mean daily wind speed (◆), by month, for August 2011 to July 2013. Data were sourced from the Broadfields meteorological station, Lincoln, Canterbury. Measurements of wind speed were taken at 10 m above ground level.

5.2.4 Experimental design

A 2x2 factorial experiment was established on a perennial ryegrass/white clover pasture at Iversen Field (I8), Lincoln University, Canterbury. Two levels (+/-) of irrigation (I) (Section 5.2.4.1) and nitrogen
fertiliser (N) (Section 5.2.4.2) were applied to the experiment site according to a randomised block design with four replicates (Table 5.4), giving 16 plots. Each plot was 5.0 x 6.0 m in size.

Table 5.4 Treatment details of perennial ryegrass/white clover experiment located in Iversen Field block I8, Lincoln University, Canterbury. Unless stated otherwise in figure captions, symbols shown below are used to differentiate the treatments.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Irrigation level</th>
<th>Nitrogen level</th>
<th>Nomenclature</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Irrigated (+I)</td>
<td>Fertilised (+N)</td>
<td>+I+N</td>
<td>□</td>
</tr>
<tr>
<td>2</td>
<td>Irrigated (+I)</td>
<td>Unfertilised (-N)</td>
<td>+I-N</td>
<td>■</td>
</tr>
<tr>
<td>3</td>
<td>Unirrigated (-I)</td>
<td>Fertilised (+N)</td>
<td>-I+N</td>
<td>○</td>
</tr>
<tr>
<td>4</td>
<td>Unirrigated (-I)</td>
<td>Unfertilised (-N)</td>
<td>-I-N</td>
<td>●</td>
</tr>
</tbody>
</table>

Pasture was sown within the experiment site on 07/01/2011 as a mixture of ‘Samson’ perennial ryegrass with AR37 endophyte at 8 kg/ha and white clover ‘Tribute’ at 4 kg/ha.

The experimental area was grazed by sheep over a 3-5 day period to a residual of 40-50 mm, whenever the ryegrass in the irrigated plots had three new fully expanded leaves per tiller. Following grazing, the plots were trimmed using a lawn mower to 40-50 mm, where necessary. Table 5.5 provides details of the time of grazing and duration of each regrowth cycle throughout the experiment. The experiment was measured from 06/08/2011 to 31/07/2013.

Table 5.5 Regrowth cycles, start and end dates from 06/08/2011 to 31/07/2013 in Iversen Field block I8 at Lincoln University, Canterbury.

<table>
<thead>
<tr>
<th>Experimental year</th>
<th>Regrowth cycle</th>
<th>Start date</th>
<th>End date¹</th>
<th>Regrowth duration (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011/12</td>
<td>1</td>
<td>06/08/2011</td>
<td>20/09/2011</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>21/09/2011</td>
<td>27/10/2011</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>28/10/2011</td>
<td>29/11/2011</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>30/11/2011</td>
<td>09/01/2012</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>10/01/2012</td>
<td>15/02/2012</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>16/02/2012</td>
<td>27/03/2012</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>28/03/2012</td>
<td>15/05/2012</td>
<td>49</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>16/05/2012</td>
<td>06/08/2012</td>
<td>83</td>
</tr>
<tr>
<td>2012/13</td>
<td>9</td>
<td>07/08/2012</td>
<td>01/10/2012</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>02/10/2012</td>
<td>07/11/2012</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>11</td>
<td>08/11/2012</td>
<td>12/12/2012</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>13/12/2012</td>
<td>14/01/2013</td>
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<td>13</td>
<td>15/01/2013</td>
<td>11/02/2013</td>
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<td></td>
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<td>12/02/2013</td>
<td>21/03/2013</td>
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<td></td>
<td>15</td>
<td>22/03/2013</td>
<td>01/05/2013</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>02/05/2013</td>
<td>31/07/2013</td>
<td>91</td>
</tr>
</tbody>
</table>

Note 1: End date also indicates first day of grazing.
5.2.4.1 Irrigation

Irrigation water was applied to the +I treatment plots (Figure 5.2) when the soil moisture content (SMC) was estimated to fall below 25%, with the intention of preventing it from becoming critically limiting. A simple soil water budget was used to determine when irrigation was required:

$$\text{SMC}_e = \text{SMC}_i + \sum(R + I - \text{PET}_d)$$  \hspace{1cm} (5.1)

where the estimated soil moisture content of the soil ($\text{SMC}_e$) is equal to the last measured soil moisture content ($\text{SMC}_i$) plus the sum of the daily rainfall ($R$) and irrigation ($I$) minus PET$_d$ (mm/d), since the last soil moisture measurement.

Irrigation water was applied using a soaker hose at a rate of 25 mm/h. Irrigation was generally applied within the first two weeks after grazing. No more than 25 mm of water was applied per plot, per day, except on 12/01/2011 when 50 mm was required to increase the SMC above the critical level. Irrigation following periods of heavy rain was avoided to prevent ponding or redistribution of water on the soil surface and to minimise the potential for drainage below the SMC measurement depth of 500 mm. A summary of the amount and timing of irrigation is given in Figure 5.2.

Surface infiltration rates of Wakanui silt loam soils within the Lincoln area have been reported to range between 2.2 and >400 mm/h. Based on the findings by Hermawan (1990), however, the steady state infiltration rate may be closer to ~15 mm/h (Section 2.3.3.2), lower than the rate at which irrigation was applied within the current experiment. Accordingly, surface ponding and/or redistribution of water may have occurred. Results of soil-water flow modelling at the experiment site are provided in Section 5.3.5, and address the potential for the redistribution of water.

5.2.4.2 Nitrogen

Nitrogen (N) fertiliser was applied to the +N treatment plots immediately following each grazing. Fertiliser was applied in the form of Urea (46% N) at a rate of 50 kg N/ha per application. In total there were 8 x 50 kg N/ha applications of fertiliser each year, totalling 400 kg N/ha/y per plot and 800 kg N/ha over the experimental period.

5.2.5 Measurements

5.2.5.1 Dry matter production

Herbage mass (HM, kg DM/ha) was measured using a Jenquip rising plate meter (RPM). Ten plate meter readings per plot were taken on each measurement date, from which the average RPM value for each plot was determined. The plate meter readings were converted to herbage mass values using a RPM calibration equation for each regrowth interval (Section 5.2.7.1). In total 91 measurements of herbage mass were made for each treatment plot over 16 regrowth cycles.
Calibration of the plate meter was achieved by, on each measurement date, taking two RPM readings within a 0.2 m² representative quadrat area per plot. The pasture in each quadrat was clipped using battery powered sheep shears to a residual height of 10-20 mm. The cut pasture samples were oven dried at 65°C for a minimum of 48 hours then weighed. The herbage mass of each quadrat was determined using Equation 3.3.

For each regrowth cycle, the average quadrat RPM readings were paired with measurements of herbage mass and a linear regression analysis performed to determine the calibration regression equation. Results of the regrowth cycle calibrations used were given by Black and Murdoch (2013) and are summarised in Section 5.2.7.

5.2.5.2 Herbage nitrogen
The herbage nitrogen content was determined using near-infrared spectroscopy (NIR) at the Lincoln University analytical laboratory from the dried herbage for each treatment plot at the end of each regrowth cycle.

5.2.5.3 Volumetric soil water content
The volumetric water content of the soil (θ, mm³/mm³) was measured at 1-2 weekly intervals over the experiment using a Time Domain Reflectometer (TDR) (Trace System, Soil Moisture Equipment, USA) with steel probes installed to 500 mm depth in the centre of each plot (Section 2.3.3.3). In total, 91 measurements were made per plot over the experiment, giving 1,456 SMC measurements. This enabled differences in soil moisture among treatments to be observed over time, and for frequent calculations of water use (Section 5.3.6.1) and water use efficiency (Section 5.3.6.2).

5.2.6 Modelling

5.2.6.1 Pasture growth modelling, Iversen Field
DairyMod (Johnson et al., 2008) was calibrated against lysimeter-measured perennial ryegrass pasture growth at Larundel Dairy Farm, West Eyreton, Canterbury (Section 3.3.8). In the current chapter, the calibrated model is validated using the Lincoln experiment against measured herbage yield data from the perennial ryegrass/white clover ±irrigation and ±dryland treatment pastures.

Single paddock simulations for each plot were run over a 10-year period (2003-2013) although only data from 2011-2013 were analysed, in line with that measured. Simulations were run with 10 ‘loops’ to reduce the influence of the initial conditions (Johnson, 2013b). Parameters were set within the management module of the model to replicate the management of the pasture at the experiment site. For example, set grazing dates were used over the experimental period (Table 5.5). Daily climate data inputs of air temperature, solar radiation, wind speed, vapour pressure and precipitation were sourced from the Broadfields meteorological site (Section 5.2.2). Irrigation applied to the +I pastures (Section
5.2.4.1) was added to the daily rainfall totals. Nitrogen fertiliser was applied immediately following each grazing at the rate of 50 kg N/ha (Section 5.2.4.2). For the unfertilised pastures, an initialisation period of 10 years with 10 loops with N fertiliser applied was followed by a single loop simulation for the period 2011-2013 with no N fertiliser (Johnson, 2013b).

Within the biophysics water module, the soil hydraulic and physical properties were defined. The soil layers in Table 5.1 were condensed to three layers (as required by the model): 0-200 mm, 200-400 mm and 400-500 mm. The layers approximately corresponded to changes in textural layers detailed by Watt and Burgham (1992). $K_{sat}$, $\theta_s$, and $\theta_r$ values were those used and tested in the HYDRUS simulations (Section 5.2.6.2) from soil water retention measurements for a Wakanui silt loam soil, taken 1.4 km east of the experiment site, given by Greenwood (1989) (Table 5.1). Field capacity and wilting point values for the individual layers were estimated from water retention curve data (Appendix 25), derived from modified soil hydraulic parameters estimated for the HYDRUS simulations (Section 5.2.6.2). Soil water potentials of -10 kPa for field capacity and -1,500 kPa for wilting point were used (McLaren & Cameron, 1996). The retention data confirmed a field capacity of ~35% as reported by Black and Murdoch (2013) (Section 5.2.2), but indicated a wilting point closer to 15%. According to Watt and Burgham (1992), the clay composition of the soil is about 25%.

Site-specific parameters that may vary from those applied in the calibrated model (Section 3.2.6.1) include the residual biomass, the rooting depth and the temperature stress functions relating to white clover. At LDF, a residual pasture height of 50-60 mm equated to ~1 t DM/ha (Section 3.2.5.1), therefore this has been assumed, initially, to also apply to the 50 mm residual for the Lincoln experiment. The rooting depth of the pasture was unknown, and the potential rooting depth was unrestricted compared with in the lysimeter experiment where the base of the lysimeters restricted roots to a maximum of 700 mm. Clover was excluded from the calibrated model, but was observed as present at the Lincoln experiment site. Accordingly, an analysis to determine appropriate rooting depths for the ryegrass and clover pasture components and the white clover temperature functions was required.

**Site-specific parameter testing overview**

Testing of the site-specific parameters was carried out for the ryegrass-based fertilised and irrigated (+I+N) pastures, then applied to the remaining three treatments (-I+N, +I-N and -I-N). Appropriate rooting depths for the dryland pastures were tested.

The ranges tested for each of the parameters were based on a combination of the model default values, values reported in the literature and iterative adjustment of the parameters sufficient to allow a trend to be identified (Table 5.6). The model dictated the change increments applied to each of the parameters tested.
Post-grazing residuals of 0.8-1.6 t DM/ha were assessed, based on typical grazing residuals reported in the literature (Section 2.3.2.5) to determine whether the assumption of 1 t DM/ha was appropriate. Rooting depths of 300-1100 mm were tested based on those reported in the literature (Section 2.3.2.1). High and low temperature stress functions for white clover were tested as both active and inactive. When active, the temperature stress ranges given in Table 5.6 were tested.

Table 5.6 Parameter testing comparing post-grazing herbage residuals, rooting depths, temperature and stress functions, clay content and wilting point values in DairyMod simulations for the +I+N pastures, and rooting depths for the -I+N pastures at Lincoln University. Treatment acronyms were given in Table 5.4.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Range tested</th>
<th>Change increments</th>
<th>NSE</th>
<th>NRMSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual biomass (t DM/ha)</td>
<td>0.8-1.6</td>
<td>0.1</td>
<td>-0.43-0.40</td>
<td>0.34-0.52</td>
</tr>
<tr>
<td>Ryegrass irrigated</td>
<td></td>
<td></td>
<td>0.40-0.41</td>
<td>0.33-0.34</td>
</tr>
<tr>
<td>White clover irrigated</td>
<td></td>
<td></td>
<td>0.39-0.40</td>
<td>0.33-0.34</td>
</tr>
<tr>
<td>Ryegrass dryland</td>
<td>300-1100</td>
<td>100</td>
<td>0.54-0.58</td>
<td>0.45-0.47</td>
</tr>
<tr>
<td>White clover dryland</td>
<td></td>
<td></td>
<td>0.55-0.64</td>
<td>0.41-0.47</td>
</tr>
<tr>
<td>No temperature stress</td>
<td></td>
<td></td>
<td>0.41</td>
<td>0.33</td>
</tr>
<tr>
<td>Low, initial</td>
<td>-7-0</td>
<td>1</td>
<td>0.17-0.40</td>
<td>0.33-0.39</td>
</tr>
<tr>
<td>Low, full</td>
<td>-10-0</td>
<td>1</td>
<td>-0.67-0.17</td>
<td>0.39-0.56</td>
</tr>
<tr>
<td>Low, sum for recovery</td>
<td>0-100</td>
<td>10</td>
<td>0.40-0.40</td>
<td>0.33</td>
</tr>
<tr>
<td>High, initial</td>
<td>25-34</td>
<td>1</td>
<td>0.11-0.41</td>
<td>0.33-0.41</td>
</tr>
<tr>
<td>High, full</td>
<td>34-40</td>
<td>1</td>
<td>0.40-0.41</td>
<td>0.33-0.34</td>
</tr>
<tr>
<td>High, sum for recovery</td>
<td>0-100</td>
<td>10</td>
<td>0.40-0.41</td>
<td>0.33-0.34</td>
</tr>
<tr>
<td>Pm white clover (°C)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum temperature</td>
<td>1-6</td>
<td>1</td>
<td>-0.10-0.41</td>
<td>0.33-0.43</td>
</tr>
<tr>
<td>Optimum temperature</td>
<td>19-30</td>
<td>1</td>
<td>0.31-0.41</td>
<td>0.33-0.36</td>
</tr>
</tbody>
</table>

NSE is the Nash-Sutcliffe coefficient and NRMSD the normalised root mean square deviation, used to compare the simulated and observed herbage accumulation.

Simulated herbage yields were statistically compared with the observed herbage yields using the NSE coefficient and NRMSD (Section 2.5). For each tested parameter, the value that gave the highest NSE coefficient and lowest NRMSD was selected. Where the default model value gave the closest fit with the observed data, the default value was maintained (Table 5.7). A summary of the analyses is provided in Table 5.6. As discussed in Section 3.2.6.1, it is recognised that the sensitivity analysis process followed is likely to give a local rather than global optimum. However, the model prevents systematic variation of all parameters to seek a global ‘best’ combination.

Results of the sensitivity analysis for Iverson Field

Of the parameters tested, the post-grazing herbage residual resulted in the greatest range of NSE values (Table 5.6). The residual biomass that corresponded to the highest NSE value of 0.40 was 1.6 t DM/ha, suggesting that for the same residual height as LDF, there was 60% more biomass.
For the irrigated pastures, increasing the rooting depth for ryegrass and clover to 600 and 900 mm, respectively, increased the NSE to 0.41 and reduced the NRMSD to 0.33. For the dryland pastures, the NSE and NRMSD were 0.64 and 0.41, respectively, when a rooting depth of 500 mm was used for ryegrass and 700 mm for white clover. These rooting depths suggest that the pastures were abstracting water below the 500 mm soil moisture measurement depth (Section 5.2.5.3) included in the experiment. However, DairyMod does not allow more than three soil layers to be set in the model, therefore the lower layer of 400-500 mm (Table 5.8) was extended to 900 mm. Based on the soil water content at varying matric potentials and saturated hydraulic conductivity data given for a Wakanui silt loam in Table 5.1, this assumption is reasonable. The model default rooting depths are 400 mm for ryegrass and white clover.

Implementing the high and low temperature stress parameters for white clover had no effect on the overall predictions. Accordingly, the high and low temperature functions were left inactive. Changes to the default minimum and optimum \( P_m \) temperatures for white clover reduced the NSE coefficients and increased the NRMSD values; therefore, the default values of 3°C and 23°C, respectively, were maintained. Table 5.7 provides a summary of the model default pasture values and final values used in the Lincoln simulations, based on the calibrated model settings (Table 3.9) and the site-specific parameters determined for the Lincoln experiment. Table 5.8 provides a summary of the soil physical parameters applied to the irrigated and dryland pastures.
Table 5.7 Modifications to the default post-grazing herbage residuals, pasture rooting depths and stress functions in DairyMod for pasture growth simulations of irrigated and dryland perennial ryegrass/white clover pastures at Iversen Field block I8, Lincoln University, Canterbury.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>DairyMod Default</th>
<th>Irrigated</th>
<th>Dryland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-grazing herbage residual (t DM/ha)</td>
<td>-</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Rooting depth (mm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ryegrass</td>
<td>400</td>
<td>600</td>
<td>500</td>
</tr>
<tr>
<td>White clover</td>
<td>400</td>
<td>900</td>
<td>700</td>
</tr>
<tr>
<td>Low temperature stress ryegrass (°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, initial</td>
<td>FALSE</td>
<td>-1</td>
<td></td>
</tr>
<tr>
<td>Low, full</td>
<td>FALSE</td>
<td>-5</td>
<td></td>
</tr>
<tr>
<td>Low, sum for recovery</td>
<td></td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>High temperature stress ryegrass (°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High, initial</td>
<td>FALSE</td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>High, full</td>
<td>FALSE</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>High, sum for recovery</td>
<td></td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Low temperature stress white clover (°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, initial</td>
<td>FALSE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, full</td>
<td>FALSE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, sum for recovery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High temperature stress white clover (°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High, initial</td>
<td>FALSE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High, full</td>
<td>FALSE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High, sum for recovery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pm minimum temperature (°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ryegrass</td>
<td>3</td>
<td>4.5</td>
<td></td>
</tr>
<tr>
<td>White clover</td>
<td>3</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Pm optimum temperature (°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ryegrass</td>
<td>23</td>
<td>23</td>
<td></td>
</tr>
<tr>
<td>White clover</td>
<td>23</td>
<td>23</td>
<td></td>
</tr>
</tbody>
</table>

Note 1: values based on the calibrated model values (Table 3.8)

Table 5.8 Soil hydraulic property values used in DairyMod pasture growth simulations for irrigated and dryland perennial ryegrass/white clover pastures at Iversen Field block I8, Lincoln University, Canterbury.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Depth (mm)</th>
<th>Ksat (mm/d)</th>
<th>θs (%volume)</th>
<th>θr (%volume)</th>
<th>FC (%volume)</th>
<th>WP (%volume)</th>
<th>Clay content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-200</td>
<td>1608</td>
<td>48</td>
<td>0</td>
<td>37</td>
<td>17</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>200-400</td>
<td>720</td>
<td>37</td>
<td>0</td>
<td>35</td>
<td>13</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>400-900</td>
<td>36</td>
<td>32</td>
<td>0</td>
<td>31</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

Note 1: Changes in textural layers reported by Watt and Burgham (1992) were 180 mm, and 360 mm. However, DairyMod rounds to the nearest 100 mm resulting in 0-200, 200-400 and 400-900 mm layers. θs and θr are the saturated and air dry water contents, Ksat the saturated soil hydraulic conductivity, FC field capacity and WP the wilting point.

5.2.6.2 Simulating soil water flow in a field soil profile under ryegrass/white clover pasture
Both DairyMod and HYDRUS were used to simulate changes in soil moisture from 0-900 mm, drainage below the estimated maximum rooting depth of 900 mm and surface runoff of water for the 16 treatment plots at Lincoln University over the experimental period. DairyMod and HYDRUS soil moisture content predictions for the upper 500 mm soil profile were validated against average 500
mm profile soil moisture content measurements beneath ryegrass/white clover pastures of varying performance (Section 5.3.5). Validation of simulated soil moisture against measured data within the root zone is a common approach applied throughout the literature when modelling soil water flow (Jiang et al., 2010; Wöhling & Vrugt, 2007; Zhou et al., 2012). Validation of the models at the Lincoln site was an important step in the current research as, without an understanding of drainage and soil moisture changes over the rooting zone, potentially significant over-estimations in the calculation of AET (Equation 4.2) could occur. The predictive abilities of the models were quantified using the NSE and NRMSD (Section 2.5).

The HYDRUS simulations assumed one-dimensional, uniform water flow through the soil profile. Each simulation was run for a period of 726 days from 06 August 2011 through to 31 July 2013. The soil profile within each pasture plot was separated into 14 layers. Each of the first 13 layers were 50 mm in thickness and extended from 0-650 mm, corresponding to the soil water retention measurement depths given by Greenwood (1989) (Table 5.1). A base layer of 250 mm extended from 650-900 mm. No data could be found for the soil below 700 mm, therefore it was assumed that the data measured for 650-700 mm in Table 5.1 was representative of that to 900 mm. A uniform spatial discretization of $\Delta x = 1$ mm (901 nodes, 900 elements) was used for the model calculation grid.

At the soil surface, an atmospheric boundary condition with surface run-off was applied, as there was nothing inhibiting this. Daily values of potential evaporation and transpiration were calculated using the SWW model (Section 5.3.7). The SWW model was used based on the results presented in Chapter 4 and the ability to separate the processes of evaporation and transpiration (Section 2.4.2.4). Daily rainfall, to which was added irrigation for the +I pastures, was that recorded at the Broadfields meteorological site (Section 5.2.3.1). The bottom boundary condition consisted of free drainage.

The van Genuchten-Mualem soil hydraulic model (van Genuchten, 1980) was selected for the soil hydraulic properties (Section 2.3.3.4). RETC (version 6.02) (van Genuchten et al., 1991) was used to predict soil hydraulic parameters ($\alpha$, $n$, $\theta_r$, and $\theta_s$) used in the van Genuchten-Mualem model (Equation 2.32) from the soil water retention data for a Wakanui silt loam soil 1.4 km east of the experiment site given by Greenwood (1989) (Table 5.1) (Pang et al., 2008; Sarmah et al., 2006). Mualem (1976) estimated the pore connectivity parameter $l$ in the hydraulic conductivity function to average 0.5 for most soils. Saturated hydraulic conductivity values ($K_{sat}$) for each layer were taken from Watt and Burgham (1992) for a Wakanui soil, based on measurements 1.4 km north of the experiment site (Table 5.1). Table 5.9 provides a summary of the soil hydraulic parameters estimated using RETC, and $K_{sat}$ values for each 50 mm layer.
Table 5.9  Saturated hydraulic conductivity taken from Watt and Burgham (1992), and van Genuchten (1980) soil hydraulic parameters estimated using RETC from measured water retention data taken from Greenwood (1989) for a Wakanui silt loam soil, 1.4 km from the experiment site.

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Depth (mm)</th>
<th>( \theta_r ) (mm(^3)/mm(^3))</th>
<th>( \theta_s ) (mm(^3)/mm(^3))</th>
<th>( \alpha ) (1/mm)</th>
<th>n</th>
<th>l</th>
<th>( K_{sat} ) (mm/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0-50</td>
<td>0</td>
<td>0.42</td>
<td>0.0114</td>
<td>1.09</td>
<td>0.5</td>
<td>1608</td>
</tr>
<tr>
<td>2</td>
<td>50-100</td>
<td>0</td>
<td>0.48</td>
<td>0.0148</td>
<td>1.10</td>
<td>0.5</td>
<td>1608</td>
</tr>
<tr>
<td>3</td>
<td>100-150</td>
<td>0</td>
<td>0.48</td>
<td>0.0171</td>
<td>1.10</td>
<td>0.5</td>
<td>1608</td>
</tr>
<tr>
<td>4</td>
<td>150-200</td>
<td>0</td>
<td>0.48</td>
<td>0.0200</td>
<td>1.10</td>
<td>0.5</td>
<td>1608</td>
</tr>
<tr>
<td>5</td>
<td>200-250</td>
<td>0</td>
<td>0.39</td>
<td>0.0019</td>
<td>1.14</td>
<td>0.5</td>
<td>720</td>
</tr>
<tr>
<td>6</td>
<td>250-300</td>
<td>0</td>
<td>0.38</td>
<td>0.0015</td>
<td>1.14</td>
<td>0.5</td>
<td>720</td>
</tr>
<tr>
<td>7</td>
<td>300-350</td>
<td>0</td>
<td>0.35</td>
<td>0.0017</td>
<td>1.11</td>
<td>0.5</td>
<td>720</td>
</tr>
<tr>
<td>8</td>
<td>350-400</td>
<td>0</td>
<td>0.33</td>
<td>0.0013</td>
<td>1.11</td>
<td>0.5</td>
<td>36</td>
</tr>
<tr>
<td>9</td>
<td>400-450</td>
<td>0</td>
<td>0.31</td>
<td>0.0003</td>
<td>1.15</td>
<td>0.5</td>
<td>36</td>
</tr>
<tr>
<td>10</td>
<td>450-500</td>
<td>0</td>
<td>0.33</td>
<td>0.0002</td>
<td>1.17</td>
<td>0.5</td>
<td>36</td>
</tr>
<tr>
<td>11</td>
<td>500-550</td>
<td>0</td>
<td>0.34</td>
<td>0.0002</td>
<td>1.21</td>
<td>0.5</td>
<td>48</td>
</tr>
<tr>
<td>12</td>
<td>550-600</td>
<td>0</td>
<td>0.34</td>
<td>0.0002</td>
<td>1.18</td>
<td>0.5</td>
<td>48</td>
</tr>
<tr>
<td>13</td>
<td>600-650</td>
<td>0</td>
<td>0.35</td>
<td>0.0004</td>
<td>1.16</td>
<td>0.5</td>
<td>48</td>
</tr>
<tr>
<td>14</td>
<td>650-900(^1)</td>
<td>0</td>
<td>0.35</td>
<td>0.0003</td>
<td>1.18</td>
<td>0.5</td>
<td>48</td>
</tr>
</tbody>
</table>

Note 1: Soil layer values based on measured water retention and saturated hydraulic conductivity data for 650-700 mm in Table 5.1, but assumed to represent the soil down to 900 mm.

\( \theta_r \) and \( \theta_s \) are the residual and saturated water contents, \( K_{sat} \) the saturated soil hydraulic conductivity, \( l \) the tortuosity parameter in the conductivity function and \( \alpha \) and \( n \) parameters in the soil water retention function.

Root water uptake was simulated using the Feddes water uptake reduction model (Feddes et al., 2001; Feddes et al., 1978) (Section 2.3.3.4). Root water uptake parameters used in the calibrated model at LDF were applied at the Lincoln experiment site (Table 4.3). The critical stress water uptake index (or root adaptability factor) was set to zero to allow fully compensated root water uptake. The minimum allowed pressure head at the soil surface, below which soil evaporation is restricted, was set at a suction of -1500 kPa.

**Site-specific parameter testing overview**

Testing of the site-specific soil hydraulic parameters in Table 5.9 was carried out for the ryegrass-based fertilised and irrigated (+I+N) pastures to determine if they were representative at the experimental site. The tested parameters were then applied to the remaining three treatments (-I+N, +I-N and -I-N). Parameters were adjusted according to the intervals specified in Table 5.10. The estimated soil hydraulic parameters in Table 5.9 were initially assumed then iteratively decreased and increased on a percentage basis, as detailed in Table 5.10, to allow a trend to be identified.

Simulated average soil moisture contents of the upper 500 mm soil profile were statistically compared with the treatment average observed soil moisture data using the NSE and RMSD (Section 2.5). For
each tested parameter, the value that gave the highest NSE coefficient and lowest RMSD was selected. Table 5.10 and Appendix 26 provide summaries of the sensitivity analyses performed, and the resultant NSE and RMSD values. As identified in Section 4.2.4.1, HYDRUS enables soil hydraulic properties to be determined using an inverse solution function. However, the model allows no more than 15 properties to be tested simultaneously, and this is at the upper end of what is suggested. Accordingly, this was not appropriate given the number soil layers modelled (Table 5.9), and therefore it is possible that a local rather than global optimum was achieved due to the incremental, iterative approach taken.

Table 5.10 Site specific parameter testing assessing the effects of adjusting the soil hydraulic parameters on HYDRUS soil water flow predictions for irrigated and fertilised perennial ryegrass/white clover pastures at Iversen Field block 18, Lincoln University, Canterbury.

<table>
<thead>
<tr>
<th>Soil hydraulic parameters&lt;sup&gt;1,2&lt;/sup&gt;</th>
<th>Range tested</th>
<th>Change increments</th>
<th>NSE</th>
<th>NRMSD</th>
</tr>
</thead>
<tbody>
<tr>
<td>θ&lt;sub&gt;r&lt;/sub&gt; (mm&lt;sup&gt;3&lt;/sup&gt;/mm&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>0 – 0.1</td>
<td>0.02</td>
<td>-0.16-0.42</td>
<td>0.11-0.15</td>
</tr>
<tr>
<td>θ&lt;sub&gt;s&lt;/sub&gt; (mm&lt;sup&gt;3&lt;/sup&gt;/mm&lt;sup&gt;3&lt;/sup&gt;)</td>
<td>80-120%</td>
<td>10%</td>
<td>-0.75-0.42</td>
<td>0.11-0.30</td>
</tr>
<tr>
<td>α (1/mm)</td>
<td>50-150%</td>
<td>25%</td>
<td>0.25-0.55</td>
<td>0.10-0.12</td>
</tr>
<tr>
<td>n</td>
<td>95-105%</td>
<td>1%</td>
<td>-1.62-0.63</td>
<td>0.09-0.23</td>
</tr>
<tr>
<td>K&lt;sub&gt;sat&lt;/sub&gt; (mm/d)</td>
<td>50-150%</td>
<td>25%</td>
<td>0.46-0.63</td>
<td>0.09-0.10</td>
</tr>
<tr>
<td>/</td>
<td>0.40-0.60</td>
<td>0.05</td>
<td>0.62-0.63</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Note 1: Range tested refers to the relative values of the assessed parameters to the default parameters given in Table 5.9, except for θ<sub>r</sub>, for which the absolute value tested is given.

Note 2: Parameters α, n and / are empirical coefficients affecting the shape of the hydraulic functions, K<sub>sat</sub> is the saturated hydraulic conductivity, θ<sub>s</sub> is the saturated soil water content, and θ<sub>r</sub> is the residual or air-dry soil water content.

NSE is the Nash-Sutcliffe efficiency and NRMSD the normalised root mean square deviation, used to compare the simulated and observed soil moisture content for the 500 mm soil profile.

Results of the site-specific parameter testing

For the +I+N pastures, the default soil hydraulic parameter values in Table 5.9 resulted in the highest NSE coefficients and lowest RMSD values (Appendix 26), except for ‘α’ and ‘n’, both of which affect the shape of the water retention curve. When the values for ‘α’ in Table 5.9 were reduced by half, the NSE increased from 0.42 to 0.55 and the RMSD reduced from 0.11 to 0.10. When ‘n’ was increased by 1%, the NSE coefficients increased by a further 0.08 from 0.55 to 0.63 and the NRMSD decreased from 0.10 to 0.09.

5.2.7 Calculations

5.2.7.1 Herbage mass

Figure 5.5 summarises the coefficients of calibration equations that were used to estimate herbage mass for each of the 16 regrowth cycles (Table 5.5) from the calibration quadrant herbage mass and RPM data (Black & Murdoch, 2013). For 14 of the 16 regrowth cycles, linear regression models
provided appropriate fits and were unaffected by N fertiliser. For Regrowth 7, a quadratic model was required and Regrowth 5 was affected by N (P<0.001). Coefficients of determination ($r^2$) were between 0.53 and 0.94.

![Figure 5.5 Coefficients of calibration equations a (◇), b (◆) and c (□) for a rising plate meter (RPM) used to estimate herbage mass of a perennial ryegrass/white clover sward at Lincoln, over 16 continuous regrowth cycles between 06/18/2011 and 31/07/2013. Normally calibrations were linear, unaffected by nitrogen (N) fertiliser and irrigation ($y = a + bx$, where $y$ is herbage mass and $x$ is RPM reading). Regrowth 7 required a quadratic model ($y = a + bx + cx^2$) and for Regrowth 5 the linear model was affected by ±N ($y_{-N} = a_{-N} + b_{-N} \times x$ and $y_{+N} = [a_{-N} + a_{+N}] + [b_{-N} + b_{+N}] \times x$. Sourced from Black and Murdoch (2013)).

The total yield (TY, kg DM/ha) for each regrowth interval, being the change in herbage mass since the last grazing date, was calculated from the pre-grazing herbage mass minus the residual or post-grazing herbage mass. The herbage mass accumulation during grazing, which occurred for 3-10 days, was assumed zero.

5.2.7.2 Thermal time and temperature adjusted growth rates

Thermal time (Tt) was calculated using the method provided by Jones and Kiniry (1986), for which a sinusoidal function is fitted to mean daily air temperature, where it exceeds $T_b$ (Section 2.3.2.3 and Equation 2.3). Air temperature data from Broadfields (Section 5.2.3.2), recorded at 10-minute intervals, was used to calculate Tt with $T_b = 3^\circ C$ and $T_{opt} = 23^\circ C$, in line with the results of DairyMod sensitivity analysis (Table 5.7) and values reported in the literature (Section 2.3.2.3). Tt values were summed to give daily values, and accumulated over 1-2 week periods, based on herbage yield measurements.

Temperature adjusted growth rates (TAGR) were determined from the slope of the relationship between accumulated total herbage yield and accumulated Tt (Section 5.2.8).
5.2.7.3 Total soil water content

The total soil water content ($\theta$, mm) for the soil profile was calculated by multiplying the profile depth of 500 mm by the volumetric water content of the soil.

5.2.7.4 Actual evapotranspiration

AET was calculated over the rooting zone of 900 mm, based on the results of the DairyMod parameter testing (Table 5.7), for each of the 16 treatment plots. AET was calculated between each successive soil moisture measurement using a simple water balance approach (Equation 4.2) based on that given by Russell and Norman (1959).

Rainfall (R) data were sourced from the Broadfields meteorological station (Figure 5.2). Irrigation depths applied were recorded on site (Figure 5.2). Changes in the soil water content ($\theta$) from 0-500 mm were measured throughout the experiment (Section 5.3.5.1) and from 500-900 mm were modelled using HYDRUS (Section 2.3.3.4). Drainage and surface water run-off were also modelled using HYDRUS.

Mean daily AET rates (AET$_{daily}$, mm/d) were calculated for each regrowth cycle by dividing the total AET per regrowth cycle (mm) by the cycle duration (d).

5.2.7.5 Potential evapotranspiration

The daily PET$_c$ for the treatment pastures were estimated using a number of methods, which were then compared. The DairyMod model outputs of evapotranspiration were firstly analysed. The mean lysimeter monthly average $K_c$ time series developed from AET (with potential drainage) (Figure 4.19) and the mean lysimeter SWW-PET$_c$-derived time series (Figure 4.18) in Chapter 4 were used to estimate PET$_c$ with Equation 2.37. Daily PET$_c$ estimates used were those given in Figure 5.2. The DairyMod and $K_c$ PET$_c$ predictions were then compared with predictions using the SWW model, which had previously provided the most accurate estimates of PET$_c$ in the lysimeter experiments (Section 4.3.5).

The SWW model (Equations 2.47-2.54) was used to calculate daily potential from the 16 perennial ryegrass/white clover pasture plots. The model requires daily climatological inputs (solar radiation, air temperature, relative humidity and wind speed) and daily biophysical inputs of canopy leaf area index (LAI) and height (h) (Section 2.4.2.4).

Daily climate data were sourced from the Broadfields meteorological station (Section 5.2.3). Daily LAI and h values were estimated from RPM readings (Section 5.2.5.1), using the equations derived from the linear regression of h (y-axis) against RPM heights (x-axis) and LAI (y-axis) against h (x-axis) at Larundel Dairy Farm (not shown), as follows:

$$h \text{ (mm)} = 1.84 \times \text{RPM} - 4.16$$
The SWW method includes the assumption that the supply of water to the plant is such that transpiration is not restricted (Section 2.4.2.4). Where the SMC becomes limiting, therefore, SWW will over-estimate the actual rate of canopy transpiration. However, within HYDRUS daily inputs of SWW-derived evaporation and transpiration are adjusted according to the soil moisture status, based on a minimum allowed pressure head at the soil surface and Feddes et al. (1978) root water uptake parameters (Table 4.2). Accordingly, for plots where the SMC was limiting, the HYDRUS-adjusted SWW PET values (SWW PET\textsubscript{adj}) were adopted (Section 5.3.7).

5.2.7.6 Water-use efficiency

Water-use efficiency (WUE) (kg DM/mm) was determined from the slope of the relationship (Section 5.2.8) between the measured accumulated total herbage yield and accumulated actual evapotranspiration, calculated using Equation 4.2.

5.2.8 Statistical Analysis

Statistical analysis of the data was conducted in GenStat (version 17, VSN International Ltd, 2013).

Annual total herbage yields, simulated drainage depths, calculated AET, estimated PET\textsubscript{a}, SMC measurements and AET over each regrowth cycle were analysed using two-way ANOVA procedures in randomised blocks, with irrigation and nitrogen as the treatment effects. Where treatment means were significant (α=0.05), they were separated using Fisher’s protected least significant difference (LSD) test. Unless otherwise specified, standard errors of the mean (SEM) were used to describe variation in the data within treatments. SEM values associated with simulated annual and regrowth cycle-based drainage depths and runoff were small (SEM=0.1 mm), and therefore have not been included in the presentation of results (Section 5.3.5.2). Similarly, SEM values associated with annual AET calculations and PET\textsubscript{a} estimates were small (<2 mm), and so too have not been included in the presentation of results (Section 5.3.6).

A split-line regression model was fitted to the herbage yield and Tt data for each of the 16 plots to quantify the TAGRs (slopes of the fitted relationships), and when they changed throughout the year. TAGRs for the 16 plots were then analysed using ANOVA procedures to test the effects of irrigation and N fertiliser.

A simple linear regression model was used to quantify the WUE for each of the 16 plots from the relationship of accumulated herbage yield against accumulated AET each year. In the second year (2012/13) a split-line regression model was fitted to the WUE data of the -I pastures. The annual WUE values were analysed using ANOVA procedures to test the effects of irrigation and N fertiliser.
Validation of DairyMod for simulating pasture growth was carried out through comparison of annual and regrowth cycle-based simulated and measured herbage mass for each of the pastures. The use of DairyMod and HYDRUS for the simulation of soil water flow was validated at the Lincoln site through comparison of simulated and observed soil moisture data for the upper 0-500 mm soil profile for each measurement date (Wöhling & Vrugt, 2007; Zhou et al., 2012). Predictions of PET\textsubscript{c} using the DairyMod model, K\textsubscript{c} time series from Chapter 4 and the SWW model were validated against measured AET. The goodness of fit of each of the HYDRUS, DairyMod and PET\textsubscript{c} predictions with measured data was determined using the NSE coefficient and the RMSD, normalised to the mean of the observed data (Equations 2.55-2.57). Simulated outputs that generated the highest NSE coefficient and lowest RMSD/NRMSD were deemed to provide the best fit with the observed data.

To gain further insight into causes of the DairyMod and HYDRUS model deviations from the observed data, the MSD was partitioned into the squared bias (SB), non-unit slope (NU) and lack of correlation (LC), as given by Equations 2.58-2.61.

Where data are presented in tables, italicised font has been used to distinguish simulated results from measured data, for which normal font has been maintained.
5.3 Results

5.3.1 Herbage dry matter production

As expected, annual herbage dry matter production across the two year experiment was affected by irrigation (P<0.001) and nitrogen (P<0.001) (Figure 5.6). In 2011/12 the +N pastures (19.1±0.42 t DM/ha/y) produced 6.6 t DM/ha/y more biomass than the -N pastures (12.5±0.42 t DM/ha/y) and, the +I pastures (17.4±0.42 t DM/ha/y) produced 3.1 t DM/ha/y more than the -I pastures (14.3±0.42 t DM/ha/y). Similarly, in 2012/13 the +N (13.1±0.33 t DM/ha/y) and +I (13.4±0.33 t DM/ha/y) pastures produced 3.6 and 4.2 t DM/ha/y more herbage mass than the -N (9.5±0.33 t DM/ha/y) and -I (9.2±0.33 t DM/ha/y) pastures, respectively. In 2011/12 the dominant effect was nitrogen, accounting for 76% of the SEr compared with 17% for irrigation. In 2012/13 irrigation became the dominant effect, accounting for 52% of the SEr compared with 39% for nitrogen.

Full details of the total herbage yields for each regrowth cycle, with treatment effects, are given in Appendix 27.

![Figure 5.6 Accumulated herbage yield of perennial ryegrass pastures at Lincoln University, Canterbury, for the periods 06/08/2011-06/08/2012 and 07/08/2012-31/07/2013. Treatments are +I+N (□), +I-N (■), I+N (○) and -I-N (●). Error bars are the SEM for the irrigation (I) and nitrogen (N) effects on total herbage yield. Treatment acronyms were given in Table 5.4. Yield data were sourced from Black and Murdoch (2013).](image)

5.3.2 Temperature adjusted growth rates

The TAGR of the pastures differed in response to both nitrogen and irrigation (Figure 5.7, Table 5.11). Annually, the TAGR of the +N pastures exceeded (P<0.001) that of the -N pastures by 2.4 kg DM/ha/^Cd or 52% (2011/12) and 1.3 kg DM/ha/^Cd or 35% (2012/13). The annual TAGR of the +I pastures also exceeded (P<0.022) that of the -I pastures by 1.1 kg DM/ha/^Cd or 21% (2011/12) and 1.5 kg DM/ha/^Cd or 42% (2012/13). In 2012/13 the annual average TAGR was influenced by an I*N
interaction (P=0.01), but it accounted for <3% of the SS. In both years there was a change in the TAGR of all pastures between November and January, where the TAGR reduced. In 2011/12, the TAGR for the -N pastures changed on the 30/11/2011, whereas the date of change for the +N pastures varied with irrigation (Figure 5.7). The TAGR of the +I+N pastures did not change until 07/01/2012, one month later than that for the -I+N pastures. In 2012/13, the TAGR of the +I pastures reduced 2-3 weeks later than that for the -I pastures. The observed changes were in response to soil moisture deficits, which has been discussed in Section 5.4.1.2.

Figure 5.7 Influence of N fertiliser and irrigation on the relationship between accumulated total herbage yield and accumulated thermal time (Tt) of perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the periods 06/08/2011-06/08/2012 (2011/12) and 07/08/2012-31/07/2013 (2012/13), above a base temperature of 3°C. Treatments are +I+N (□), +I-N (■), -I+N (○) and -I-N (●). Dates when the temperature-adjusted growth rates (TAGR) (slopes of lines) changed are indicated. Treatment acronyms were given in Table 5.4. Yield data were sourced from Black and Murdoch (2013).
Table 5.11 Influence of irrigation and N fertiliser on temperature adjusted growth rates (TAGR) (kg DM/ha/°C/d) of perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the periods 06/08/2011-06/08/2012 (2011/12) and 07/08/2012-31/07/2013 (2012/13), above a base temperature of 3°C. Treatment acronyms were given in Table 5.4.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2011/12</th>
<th></th>
<th></th>
<th></th>
<th>2012/13</th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>06 Aug -</td>
<td>Nov-Jan¹</td>
<td>Nov-Jan¹ -</td>
<td>06 Aug</td>
<td>Annual</td>
<td>06 Aug -</td>
<td>Nov-Dec²</td>
<td>Nov-Dec² -</td>
</tr>
<tr>
<td>+I+N</td>
<td>10.8</td>
<td>5.0</td>
<td>7.5</td>
<td>10.2</td>
<td>3.4</td>
<td>5.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+I-N</td>
<td>8.6</td>
<td>3.6</td>
<td>5.2</td>
<td>7.5</td>
<td>2.7</td>
<td>4.3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-I+N</td>
<td>11.8</td>
<td>3.8</td>
<td>6.5</td>
<td>10.5</td>
<td>0.9</td>
<td>4.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-I-N</td>
<td>8.5</td>
<td>2.0</td>
<td>4.0</td>
<td>8.4</td>
<td>0.8</td>
<td>3.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>NS</td>
<td>&lt;0.002</td>
<td>0.022</td>
<td>0.013</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>0.007</td>
<td>&lt;0.001</td>
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<td></td>
</tr>
<tr>
<td>I*N</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
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<td>0.029</td>
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<tr>
<td>SEM*¹N</td>
<td>0.54</td>
<td>0.33</td>
<td>0.39</td>
<td>0.20</td>
<td>0.13</td>
<td>0.10</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: The dates when TAGR changed ranged from 30/11/2011-07/01/2012 (1) and from 25/11/2012-13/12/2012 (2)

5.3.3 Herbage nitrogen

The nitrogen content ranged from 2.0-3.6% in the +I+N pastures, 1.6-3.4% in the +I-N pastures, 1.8-3.7% in the -I+N pastures and 1.6-3.4% in the -I-N pastures (Figure 5.8). Over the experiment, main effects of irrigation (P<0.001) and nitrogen (P=0.002) resulted in mean nitrogen contents of 2.69±0.064%, 2.41±0.064%, 2.65±0.064% and 2.44±0.064% for the +I, -I, +N and -N pastures, respectively.

For Regrowths 3, 4, 9 and 10 there were no differences (0.107<P<0.731) in the measured nitrogen concentrations across all treatments. For 11 of the remaining 12 regrowths (Regrowths 1, 2, 5-8 and 11-15) main effects of irrigation (<0.001<P<0.045) and nitrogen (<0.001<P<0.045) were evident. For Regrowth 16, there was an I*N interaction. However, the interaction accounted for only 6% of the SSr compared with 89% by the main effect of N. Full details of nitrogen content of the pastures for each regrowth cycle, with treatment effects, are given in Appendix 28.

NNI values for the pastures ranged from 0.22-1.03 over the experiment, and indicated that nitrogen was non-limiting in the +I+N pastures for 13 of the 16 regrowths (Regrowths 1-3, 6-10 and 12-16) and during Regrowths 1, 3, 8, 9, 15 and 16 for the -I+N pastures (Figure 5.8). For the +I-N pastures and -I-N pastures, nitrogen was non-limiting for six (Regrowths 5, 6, 9, 12, 14 and 16) and two (Regrowths 9 and 16) of the regrowth cycles, respectively.
Nitrogen content (N%) (a) and the nitrogen nutrition index (NNI) (b) of perennial ryegrass/white clover pastures at Lincoln University Farm, Canterbury, for the period 06/08/2011-31/07/2013. Treatments are +I+N (□), +I-N (■), -I+N (○) and -I-N (●). Treatment acronyms were given in Table 5.4. Each point represents the N% or NNI at the end of a full regrowth cycle. The error bar shows the maximum standard error of the mean for pasture N% measurements. The horizontal black line represents the optimum NNI of 1.0 (—), and the dashed black line (—--) represents an NNI of 0.8, below which N is limiting to growth.

5.3.4 Modelled pasture growth

Using the calibrated model from Chapter 3 with site specific adjustments (Section 5.2.6.1), DairyMod over and under-estimated herbage accumulation throughout the experiment (Figure 5.9a-b, Table 5.12). For example, the simulated yield of the +I+N pastures was 17.8 t DM/ha in 2011/12, 13% less than that measured but in 2012/13 it was 21% more than that measured. Despite no nitrogen applied to the -N pastures over the experimental period, the simulated average total herbage yields were approximately equal to the +N pastures, with maximum differences of 0.6 t DM/ha/y, and suggests that the model did not account for variations in N supply, which was also observed in the lysimeter experiment for LDF (Section 3.4.1.7). The result was over-estimations of herbage accumulation by DairyMod of 26-65% in the -N pastures (Figure 5.9a-b, Table 5.12).

For the +I+N and -I+N pastures, NSE coefficients of 0.41 and 0.64 and NRMSD values of 0.33 and 0.41 were achieved, respectively (Table 5.12). Both had reasonably well distributed biases with LC contributing 92-98% of the MSD. The -N pastures had lower NSE coefficients (<0) and higher NRMSD (0.61-0.82) compared with the +N pastures. SB values of 50% and 32% and NU values of 15% and 23% were in response to the over-estimation of yields throughout the experiment.

The predicted yields could, however, be improved through adjustment of parameters set by the calibrated model in Chapter 3, specifically the high temperature functions for ryegrass. The optimum temperature (\(T_{\text{opt}}\)) for \(P_n\) was firstly adjusted in 1°C increments. The low and high temperature stress parameter settings were then also incrementally increased by 1°C (\(T_{\text{mx,low}}\) and \(T_{\text{mx,high}}\)) and 10°C.
(T_{\text{sum, high}}), as per the sensitivity analysis in Chapter 3 (Section 3.2.6.1). The analysis identified that reducing T_{\text{min}} to 33°C, inactivating the low temperature ryegrass stress functions and adjusting T_{\text{mx, low}}, T_{\text{mx, high}} and T_{\text{sum, high}} to 24°C, 28°C and 20°C (sum) improved yield estimations for the +N pastures (Figure 5.9c-d, Table 5.12). Reducing T_{\text{min}} to 33°C, inactivating the low temperature ryegrass stress functions and adjusting T_{\text{mx, low}}, T_{\text{mx, high}} and T_{\text{sum, high}} to 26°C, 29°C and 30°C (sum) improved the simulated yields of the -N pastures (Table 5.12). Table 5.13 provides a summary of the final values applied in the Lincoln experiment. When the low values ascribed to the high temperature stress parameters in the calibrated model (Chapter 3) were applied to the Lincoln experiment, temperature become more limiting than the influence of nitrogen within the model, as was identified in Section 3.4.1.7. Accordingly the model was unable to respond to changes in the applied nitrogen fertiliser. The changes to the temperature stress functions improved predictions in the Lincoln experiment, which were considered valid and therefore maintained. This has been discussed in Section 5.4.2.

Across all treatments, but to a greater extent in the +N pastures, the simulated herbage accumulation during Regrowths 1 and 9 was lower when compared with the observed, resulting in an initial offset at the start of each year. This increased in the +N pastures mid 2011/12 when the simulated herbage accumulation during Regrowths 5 and 8 reduced in the +I pastures and nearly ceased in the -I pastures.

The initial offset at the start of each season appeared to be a function of the residual herbage mass. When this was increased in the +N pastures from 1.6 t DM/ha to 3 t DM/ha for the first regrowth cycles of 2011/12 and 2012/13, and to 2 t DM/ha for the -N pastures for Regrowths 1 and 9, the initial offset was largely eliminated. While residuals of 2-3 t DM/ha are high and outside of that reported in the literature as typical (Section 2.3.2.5), plots of accumulated yield against water use indicate starting residuals of up to 2.2 t DM/ha were possible (Figure 5.19). Therefore, the adjustments to the initial herbage residuals in the model were maintained to enable the best fit with the observed data.

The reduction in the simulated herbage accumulation during Regrowths 5 and 8 was a function of water stress. During these regrowth periods, the simulated soil moisture content reduced such that the $g_{\text{water}}$ function (Figure 2.5) fell below 1.0 and growth was restricted accordingly. To minimise the effect, the transpiration stress coefficient, being a scale factor between wilting point and field capacity for the onset of water stress, was reduced incrementally from the default 0.8 to 0.4. In doing so however, the effect on pasture growth was minimal. For example, in the irrigated pastures 45 mm of water (rainfall and irrigation) was applied on 16/12/11, which was followed by a one-month period with little (<3 mm) water applied. With a transpiration stress coefficient of 0.8 this led to $g_{\text{water}}$ falling below 1.0 for the period 23/12/12 to 13/01/12 in the +I+N pastures. When the transpiration stress coefficient was reduced to 0.4, however, the result was only a small (three day) delay in the timing of water stress (not shown). Accordingly, the only way found to alleviate stress within the model was to apply irrigation just prior to the onset of water stress, although this was not done. For the -N pastures,
it appears the opposite was true, in that the transpiration stress function in the model was not as restrictive as what actually occurred, leading to the over-estimation in herbage accumulation during 2011/12. Figure 5.9c-d shows the DairyMod simulated yields following adjustments to the calibrated model temperature stress functions for perennial ryegrass, with the increase in the residual herbage for Regrowths 1 and 9. These changes have been maintained in the results presented throughout the remainder of this chapter.

Figure 5.9 Observed (symbols) and DairyMod-simulated (lines) accumulated herbage yield of perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the periods 06/08/2011-06/08/2012 and 07/08/2012-31/07/2013. Treatments are +I+N (---, □), +I-N (---, ■), -I+N (---, ○) and -I-N (---, ●). Plots (a) and (b) show the calibrated model simulated herbage yields. Plots (c) and (d) show the simulated herbage yields following adjustments to the calibrated model temperature stress functions for ryegrass and the herbage residuals for Regrowth 1 and 9. Treatment acronyms were given in Table 5.4.
Table 5.12 Summary statistics indicating DairyMod performance for herbage accumulation at Lincoln University, Canterbury for the periods 06/08/2011-06/08/2012 (2011/12) and 07/08/2012-31/07/2013 (2012/13) with the calibrated model and following adjustments to the calibrated model. Treatment acronyms were given in Table 5.4.

<table>
<thead>
<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>+I+N</td>
<td>+I-N</td>
<td>-I+N</td>
<td>-I-N</td>
<td>+I+N</td>
<td>+I-N</td>
<td>-I+N</td>
<td>-I-N</td>
</tr>
<tr>
<td>Observed</td>
<td>Total (t DM/ha)</td>
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<td>15.4</td>
<td>14.3</td>
<td>11.3</td>
<td>17.7</td>
<td>10.8</td>
<td>10.8</td>
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<td>Calibrated model</td>
<td>NSE</td>
<td>0.41</td>
<td>-0.69</td>
<td>0.64</td>
<td>-0.16</td>
<td>0.33</td>
<td>0.61</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>NRMSD</td>
<td>0.33</td>
<td>0.61</td>
<td>0.41</td>
<td>0.82</td>
<td>1, 8, 92</td>
<td>50, 15, 35</td>
<td>1, 1.98</td>
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<tr>
<td>Post adjustments</td>
<td>Total (t DM/ha)</td>
<td>18.3</td>
<td>16.1</td>
<td>14.9</td>
<td>10.1</td>
<td>16.1</td>
<td>11.6</td>
<td>12.8</td>
</tr>
<tr>
<td>to calibrated</td>
<td>NSE</td>
<td>0.51</td>
<td>0.32</td>
<td>0.70</td>
<td>0.21</td>
<td>0.30</td>
<td>0.38</td>
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</tr>
<tr>
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<td>2, 0, 98</td>
<td>0, 17, 83</td>
<td>1, 0, 99</td>
<td>2, 21, 78</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note 1: based on simulation results using the calibrated DairyMod model from Chapter 3 (Section 3.2.6.1).
Note 2: based on adjustments made to the temperature stress function for ryegrass from those in the calibrated model and the herbage residuals for Regrowth 1 and 9.

NSE is the Nash-Sutcliffe efficiency and NRMSD is the normalised root mean square deviation. The mean square deviation was separated into the squared bias (SB), the non-unit slope (NU) and lack of correlation (LC).

Table 5.13 Final parameter selection for DairyMod pasture growth simulations of irrigated and dryland perennial ryegrass/white clover pastures at Iversen Field block I8, Lincoln University, Canterbury.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Irrigated</th>
<th>Dryland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-grazing herbage residual (t DM/ha)</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Rooting depth (mm)</td>
<td></td>
<td>600</td>
</tr>
<tr>
<td></td>
<td>White clover</td>
<td>900</td>
</tr>
<tr>
<td>Low temperature stress ryegrass (°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, initial</td>
<td>24 (+N), 26 (-N)</td>
<td></td>
</tr>
<tr>
<td>Low, full</td>
<td>28 (+N), 29 (+N)</td>
<td></td>
</tr>
<tr>
<td>Low, sum for recovery</td>
<td>20 (+N), 30 (+N)</td>
<td></td>
</tr>
<tr>
<td>High temperature stress white clover (°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, initial</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Low, full</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, sum for recovery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High, initial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High, full</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High, sum for recovery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High temperature stress white clover (°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, initial</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Low, full</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low, sum for recovery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High, initial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High, full</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High, sum for recovery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pm minimum temperature (°C)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Raiang</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pm optimum temperature (°C)</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>White clover</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.3.4.1  **Canopy leaf area and height**

In response to grazing, the simulated daily height (Figure 5.10) and LAI (Figure 5.11) followed the same daily pattern as the measured data. NSE coefficients of 0.12-0.29 and NRMSD values of 0.35-0.37 when the observed and simulated LAI data were compared were indicative of a reasonably poor match (Table 5.14). For pasture height, NSE coefficients were between <0-0.21 with NRMSD of 0.42-0.53. Overall, DairyMod under-predicted the LAI of the pastures and over-predicted the height, indicating that the model did not produce enough tillers. On average, the simulated daily leaf area index was 16% less (0.5) than the measured (Table 5.14), but the high LC components of the MSD (76-79%) were indicative of a reasonably well distributed bias. The simulated mean daily canopy height had a mean daily bias of 27%, whereby the simulated height was on average 36 mm taller than that measured (Table 5.14). This was due to higher simulated residual heights of 50-220 mm compared with the measured 37-50 mm. Section 5.3.7.2 compares SWW estimated PET using observed and simulated canopy data for each of the pastures.

![Graphs showing daily observed and DairyMod-simulated canopy height with ± irrigation and ± nitrogen for perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the period 06/08/2011-31/07/2013. Treatment acronyms were given in Table 5.4.](image-url)
Figure 5.11  Daily observed (—) and DairyMod-simulated (—) canopy leaf area index (LAI) with ± irrigation and ± nitrogen for perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the period 06/08/2011-31/07/2013. Treatment acronyms were given in Table 5.4.
Table 5.14  Summary statistics indicating DairyMod performance for daily estimation of leaf area index (LAI) and height (h) of perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the period 06/08/2011-31/07/2013. Treatment acronyms were given in Table 5.4.

<table>
<thead>
<tr>
<th></th>
<th>All data</th>
<th>+I+N</th>
<th>+I-N</th>
<th>-I+N</th>
<th>-I-N</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Canopy leaf area index (LAI)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured LAI range</td>
<td>0.9-8.7</td>
<td>0.9-8.7</td>
<td>1.72</td>
<td>0.9-8.7</td>
<td>0.9-7.3</td>
</tr>
<tr>
<td>Modelled LAI range</td>
<td>0.8-6.6</td>
<td>1.1-6.6</td>
<td>0.8-6.1</td>
<td>1.1-6.6</td>
<td>0.8-6.0</td>
</tr>
<tr>
<td>Measured mean LAI</td>
<td>3.2</td>
<td>3.6</td>
<td>3.1</td>
<td>3.3</td>
<td>2.8</td>
</tr>
<tr>
<td>Modelled mean LAI</td>
<td>2.7</td>
<td>3.0</td>
<td>2.6</td>
<td>2.8</td>
<td>2.4</td>
</tr>
<tr>
<td>Mean daily bias</td>
<td>-0.5</td>
<td>-0.6</td>
<td>-0.5</td>
<td>-0.5</td>
<td>-0.4</td>
</tr>
<tr>
<td>NSE</td>
<td>0.40</td>
<td>0.44</td>
<td>0.31</td>
<td>0.47</td>
<td>0.30</td>
</tr>
<tr>
<td>NRMSD</td>
<td>0.36</td>
<td>0.35</td>
<td>0.36</td>
<td>0.36</td>
<td>0.36</td>
</tr>
<tr>
<td>SB, NU, LC (%)</td>
<td>22, 2, 77</td>
<td>19, 5, 76</td>
<td>18, 3, 79</td>
<td>12, 11, 77</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>All data</th>
<th>+I+N</th>
<th>+I-N</th>
<th>-I+N</th>
<th>-I-N</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Canopy height (h)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measured h range (mm)</td>
<td>37-371</td>
<td>37-371</td>
<td>41-307</td>
<td>37-369</td>
<td>39-311</td>
</tr>
<tr>
<td>Modelled h range (mm)</td>
<td>52-361</td>
<td>73-361</td>
<td>52-344</td>
<td>74-361</td>
<td>54-341</td>
</tr>
<tr>
<td>Measured mean h (mm)</td>
<td>135</td>
<td>152</td>
<td>131</td>
<td>140</td>
<td>118</td>
</tr>
<tr>
<td>Modelled mean h (mm)</td>
<td>171</td>
<td>188</td>
<td>166</td>
<td>175</td>
<td>156</td>
</tr>
<tr>
<td>Mean daily bias (mm)</td>
<td>36</td>
<td>36</td>
<td>35</td>
<td>35</td>
<td>38</td>
</tr>
<tr>
<td>NSE</td>
<td>0.00</td>
<td>0.21</td>
<td>-0.12</td>
<td>0.13</td>
<td>-0.53</td>
</tr>
<tr>
<td>NRMSD</td>
<td>0.46</td>
<td>0.42</td>
<td>0.46</td>
<td>0.46</td>
<td>0.53</td>
</tr>
<tr>
<td>SB, NU, LC (%)</td>
<td>30, 16, 54</td>
<td>33, 21, 46</td>
<td>32, 20, 48</td>
<td>38, 26, 36</td>
<td></td>
</tr>
</tbody>
</table>

Note: NSE is the Nash-Sutcliffe efficiency, RMSD is the root mean square deviation and NRMSD is the normalised root mean square deviation. The mean square deviation was separated into the squared bias (SB), the non-unit slope (NU) and lack of correlation (LC). The measured LAI and height data were estimated from rising plate meter measurements made throughout the experiment (Section 5.2.7.5).

5.3.4.2  Nitrogen

Despite the tendency of the model at the Lincoln field site to consistently under-estimate leaf area (Table 5.14) and under-estimate total herbage accumulation 50% of the time (Figure 5.9), the simulated nitrogen contents of the +I+N, -I+N and -I-N pastures were consistently higher than the observed, with biases of 0.34-1.12% N, although differences of up to 2% N occurred (Figure 5.12). For the -I+N pastures, DairyMod over-estimated the N content for the first 10 regrowths, but for Regrowths 11-16 the model under-estimated the N content of the pasture.
5.3.5 Soil water flow at Iversen Field block I8, Lincoln University

5.3.5.1 Observed soil moisture

The observed soil moisture over the two-year experimental period is shown in Figure 5.13. The SMC of the soil to 500 mm depth varied from at or near FC (35%) from approximately mid-June to October to below the $\theta_c$ of 24% across all treatments (Section 5.2.2). Irrigation water applied to the +I pastures, however, prevented extended periods below the $\theta_c$.

However, despite the apparent periods of water stress, herbage accumulation continued through these periods. In the -I pastures, for example, water stress was apparent for the period 19/12/2011-
5/06/2012. However, during this period the pastures produced 3.3-6.0 t DM/ha of herbage, although, this was less than the 6.3-8.6 t DM/ha produced by the +I pastures for the same period. Over a six month period in 2012/13 (November-April), the -I pastures produced 2-2.7 t DM/ha, represented by a flattening out in the herbage accumulation in Figure 5.6, compared with 6.3-8.7 t DM/ha in the +I pastures. This provides some indication that while pasture accumulation continued in the dryland pastures, it was reduced in response to limiting water conditions.

When the dates of the apparent water stress periods are compared with the dates at which the TAGR changed in each of the pastures, it appears that water was abstracted from below the measured 500 mm. For example, in 2012/13, the apparent water stress in the -I pastures commenced in the first week on November 2012. However, the TAGR did not change until the end of November. This supports the DairyMod results, which suggest that water may have been abstracted from a depth of up to 900 mm (Section 5.2.6.1).

5.3.5.2 Simulated soil water flow with DairyMod and HYDRUS

Simulated soil moisture
The observed soil moisture for the upper 500 mm is compared with the outputs from the biophysical model DairyMod in Figure 5.14 and Table 5.15. The simulated soil moisture content over the estimated rooting zone of 900 mm is also shown.

There was a general over-estimation in the SMC by DairyMod, with mean daily biases of 4-7% (20-35 mm). Calculated NSE coefficients indicated a poor fit between the simulated and observed soil moisture at less than zero, although NRMSD values of 0.17-0.33 suggested a reasonable match. When separated for each treatment, the MSDs were represented by a high SB component (65-78%), while a lack of correlation accounted for only 16-35%. Over-estimation of the SMC has the potential to increase the simulated drainage and/or run-off above what is likely to have actually occurred. Reasons for the simulated over-estimations are discussed in Section 5.4.3.
Figure 5.14 Residual analysis of observed and DairyMod-simulated soil moisture content (SMC) to 500 mm depth at Lincoln University, Canterbury, for the period 06/08/11-31/07/13. Treatments are +I+N (□), +I-N (■), -I+N (○) and -I-N (●). Treatment acronyms were given in Table 5.4. Plots show the relationship between the observed and simulated SMC where solid lines (―) show the 1:1 relationship and dotted lines (---) are the fitted lines (left), the observed SMC (symbols) and simulated SMC for 0-500 mm (—) and 0-900 mm (---) over time, with the soil moisture content at field capacity, at the critical level and wilting point indicated by the upper, mid and lower horizontal grey lines, respectively (centre), and the segmentation of the MSD into the squared bias (□), the non-unit slope (■) and the lack of correlation (●) (right). Forms of the fitted lines are (a) $y = (1.1±0.12)x - 7.6±3.92$ ($r^2=0.49$), (d) $y = (1.0±0.13)x - 6.5±4.47$ ($r^2=0.40$), (g) $y = (1.4±0.07)x - 19.1±2.18$ ($r^2=0.81$), and (j) $y = (1.4±0.08)x - 19.6±2.59$ ($r^2=0.76$).
Table 5.15 Summary statistics indicating DairyMod and HYDRUS performance in the prediction of soil moisture content at Iversen Field, Lincoln University for the period 06/08/2011-31/07/2013. Treatment acronyms were given in Table 5.4. Values in brackets represent the adjusted HYDRUS performance following changes to the soil hydraulic parameter n and/or the calibrated model pressure head at the wilting point ($h_4$).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Statistic</th>
<th>Observed</th>
<th>HYDRUS</th>
<th>DairyMod</th>
</tr>
</thead>
<tbody>
<tr>
<td>+I+N</td>
<td>Maximum (%)</td>
<td>36</td>
<td>37 (37)</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Minimum (%)</td>
<td>21</td>
<td>22 (20)</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Mean (%)</td>
<td>29</td>
<td>29 (29)</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>NSE</td>
<td>0.63 (0.63)</td>
<td>-0.44</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NRMSD</td>
<td>0.09 (0.09)</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SB, NU, LC (%)</td>
<td>2, 2, 96 (1, 4, 95)</td>
<td>65, 0, 35</td>
<td></td>
</tr>
<tr>
<td>-I-N</td>
<td>Maximum (%)</td>
<td>36</td>
<td>37 (37)</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Minimum (%)</td>
<td>21</td>
<td>22 (20)</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Mean (%)</td>
<td>28</td>
<td>29 (29)</td>
<td>33</td>
</tr>
<tr>
<td></td>
<td>NSE</td>
<td>0.53 (52)</td>
<td>-0.98</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NRMSD</td>
<td>0.11 (0.11)</td>
<td>0.22</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SB, NU, LC (%)</td>
<td>19, 1, 80 (15, 3, 82)</td>
<td>70, 0, 30</td>
<td></td>
</tr>
<tr>
<td>+I+N</td>
<td>Maximum (%)</td>
<td>36</td>
<td>37 (35)</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Minimum (%)</td>
<td>13</td>
<td>22 (16)</td>
<td>22</td>
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<td></td>
<td>Mean (%)</td>
<td>24</td>
<td>28 (24)</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>NSE</td>
<td>0.43 (0.86)</td>
<td>-0.18</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NRMSD</td>
<td>0.22 (0.11)</td>
<td>0.31</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SB, NU, LC (%)</td>
<td>64, 13, 23 (0, 6, 94)</td>
<td>78, 6, 16</td>
<td></td>
</tr>
<tr>
<td>-I-N</td>
<td>Maximum (%)</td>
<td>36</td>
<td>37 (35)</td>
<td>37</td>
</tr>
<tr>
<td></td>
<td>Minimum (%)</td>
<td>12</td>
<td>22 (16)</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Mean (%)</td>
<td>24</td>
<td>28 (24)</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>NSE</td>
<td>0.46 (0.86)</td>
<td>-0.34</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NRMSD</td>
<td>0.21 (0.11)</td>
<td>0.33</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SB, NU, LC (%)</td>
<td>61, 14, 25 (1, 7, 92)</td>
<td>77, 5, 18</td>
<td></td>
</tr>
</tbody>
</table>

Note: NSE is the Nash-Sutcliffe efficiency and NRMSD is the normalised root mean square deviation. The mean square deviation was separated into the squared bias (SB), the non-unit slope (NU) and lack of correlation (LC).

HYDRUS-simulated soil moisture over the two-year experimental period for the upper 500 mm of soil is compared with the observed in Table 5.15. The same general trends in the observed SMC were simulated in HYDRUS for each of the pastures. However, from 17 December 2012 to 21 January 2013 and from 11 February to 21 March 2013 when the observed soil moisture reached a minimum of ~12%, the simulated soil ceased drying at 22% (not shown). Accordingly, over these periods there were no changes in the simulated soil moisture resulting in the data ‘flat lining’ at 22%. This over-estimation of the soil moisture led to large SB components of 61-65%.

However, the fit of the data could be improved, and the under-estimation of soil drying largely corrected for by adjusting the point below which root water uptake within the model ceases and/or the soil hydraulic parameter n (Equation 2.32). This was achieved by incrementally decreasing the pressure head at the wilting point ($h_4$) from the calibrated model value of -800 kPa to a minimum of 1500 kPa and increasing n from the values in Table 5.9 by up to 5%.
As in the lysimeter study (Table 4.3), the effects of decreasing $h_4$ on the irrigated treatments were minimal (Table 5.15), as reasonably high soil moisture contents were maintained at the experiment site. For the dryland plots, however, decreasing $h_4$ to -1500 kPa increased the NSE from ~0.46 to 0.61 and the minimum soil water content achieved reduced to 20%.

With adjustment of the $n$ value, the NSE coefficients for the +I pastures reduced, but increased in the -I pastures. When $n$ was increased by 5%, a minimum soil moisture of 15.6% was achieved in the -I pastures and the NSE coefficients increased further to 0.86. Alternatively, to achieve similar results in the -I pastures, $h_4$ could be reduced to a pressure head of ~-10 000 kPa and $n$ maintained as per the site-specific parameter testing. Doing so eliminated the flattening out effect at low soil water contents, but in a practical sense, a value of ~-10 000 kPa is unrealistic and meant that abstraction by the pasture was not limited within the model, which is in opposition to the observed pasture growth (Figure 5.7). The need to adjust the value for $n$ in the -I pastures was likely a reflection that the soil hydraulic property data do not exactly reflect the conditions at the site rather than of model error. This has been discussed further in Section 5.4.3.1. Figure 5.14 and Table 5.15 compare the observed soil moisture with that simulated by HYDRUS, based on a value of -1500 kPa for $h_4$ and an adjusted $n$ value in the -I pastures. The soil moisture content over the estimated 900 mm rooting zone is also shown in Figure 5.14.

The HYDRUS performance was an improvement on the DairyMod simulations (Figure 5.14), as shown by higher NSE coefficients and lower NRMSD values in Table 5.15 as well as a larger proportion of the MSD being due to a general lack of correlation rather than SB or NU. A discussion of reasons for the differences in the DairyMod and HYDRUS predictions is given in Section 5.4.3.
Figure 5.15  Residual analysis of observed and HYDRUS-simulated soil moisture content (SMC) to 500 mm depth at Lincoln University, Canterbury, for the period 06/08/2011-31/07/2013. Treatments are +I+N (□), +I-N (■), -I+N (○) and -I-N (●). Treatment acronyms were given in Table 5.4. Plots show the relationship between the observed and simulated SMC where solid lines (―) show the 1:1 relationship and dotted lines (---) are the fitted lines (left), the observed SMC (symbols) and simulated SMC for 0-500 mm (—) and 0-900 mm (---) over time, with the soil moisture content at field capacity, at the critical level and wilting point indicated by the upper, mid and lower horizontal grey lines, respectively (centre), and the segmentation of the MSD into the squared bias (□), the non-unit slope (■), (■) and the lack of correlation (■) (right). Forms of the fitted lines are: (a) $y=(0.9\pm0.07)x + 3.9\pm1.9$ ($r^2=0.65$), (d) $y=(0.9\pm0.07)x +2.6\pm2.18$ ($r^2=0.60$), (g) $y=(1.1\pm0.04)x - 2.6\pm1.09$ ($r^2=0.87$), and (j) $y=(1.1\pm0.05)x - 2.8\pm1.13$ ($r^2=0.87$).
Simulated drainage

DairyMod-simulated annual drainage below 900 mm in 2011/12 and 2012/13 was estimated to be 213 mm and 457 mm (+I+N) and 238 and 467 mm (+I-N), compared with 145 and 401 mm from the -I+N pastures and 165 and 406 mm from the -I-N pastures, respectively (Figure 5.16). For the -I pastures, 100% of the drainage occurred during the months of May-October (i.e. outside the irrigation season), compared with 87% for the +I+N and 84% for the -I-N pastures. Drainage, as a percentage of annual inputs of irrigation (+I pastures only) and rainfall and was between 39-41%.

![Graph showing simulated drainage](image)

Figure 5.16 Accumulated DairyMod (——) and HYDRUS (—) simulated drainage below 900 mm soil depth from perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the periods 06/08/2011-06/08/2012 and 07/08/2012-31/07/2013. Treatment acronyms were given in Table 5.4.

The DairyMod results are compared with the drainage simulated with HYDRUS in Figure 5.16. While total annual drainage predictions by the two models are reasonably close as was also observed in Chapter 4, total drainage with DairyMod was greater for all plots during both years. DairyMod drainage was up to 30% (55 mm) and 14% (56 mm) greater than that simulated by HYDRUS in 2011/12 and 2012/13, respectively. Water appeared to drain more rapidly and was triggered earlier in the DairyMod predictions, while the drainage with HYDRUS was more continuous and gradual. This resulted in an obvious ‘start’ and ‘end’ of drainage in the DairyMod predictions, whereas the transition between drainage events by HYDRUS was smoother. For example, in response to 76.8 mm of rain from 12-15 August 2012 and a further 15.8 mm from the 19-22 August 2012, HYDRUS predicted the same amount of drainage over 29 days (13 August-10 September), while DairyMod predicted slightly less drainage...
(87.1 mm) over 21 days. With DairyMod, drainage commenced on the same day as the rain fell, while within HYDRUS, drainage was delayed by at least a day.

HYDRUS-simulated annual drainage was greatest (P<0.001) under irrigated conditions. Drainage from the +I pastures was estimated to be 182 mm in 2011/12 and 411 mm in 2012/13, compared with 148 and 360 mm from the -I pastures, respectively. In both years there was an I*N interaction. However, the effects of the interaction were minor, accounting for <0.1%. Similarly, the main effects of nitrogen accounted for <0.1% of the SS. Accordingly, irrigation was the dominant effect.

As with DairyMod, HYDRUS-simulated drainage was mostly restricted to the months of May-October. For the +I pastures, 15 mm of the simulated drainage occurred outside of these months, compared with 14 mm for the -I pastures. The greatest differences between the irrigated and dryland pastures (P<0.001) were observed at the end of each experimental year, during Regrowths 8 and 16, during which the +I pastures drained 37 and 43 mm more than the -I pastures, respectively. Drainage, as a percentage of annual inputs of rainfall and irrigation (+I pastures only) (Figure 5.2), was 34% for the +I pastures, and 36% for the -I pastures. Full details of the predicted drainage for each regrowth cycle, with treatment effects, are given in Appendix 29.

**Simulated redistribution of water at the soil surface**

In 2011/12, the DairyMod and HYDRUS-simulated runoff was negligible at ~1.3 mm and <0.1 mm, respectively (Figure 5.17). In 2012/13, run-off was predicted by DairyMod to occur on three occasions. Approximately 13 mm of run-off occurred from the +I pastures and up to 7 mm from the -I pastures on the 06/05/2013 following a 65 mm rainfall event. In June 2013, up to 0.6 mm and 1.5 mm of run-off was simulated with DairyMod to occur from each of the pastures following heavy rainfall on the 17/06/2013 and 22/06/2013, respectively (Figure 5.2). In total, the DairyMod-simulated run-off was ~15 mm from the +I pastures and ~9 mm from the -I pastures in 2012/13. As in 2011/12, the HYDRUS predicted runoff was negligible at <0.1 mm in 2012/13.
Figure 5.17  Accumulated DairyMod (—) and HYDRUS (—) simulated surface water from perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the periods 06/08/2011-06/08/2012 and 07/08/2012-31/07/2013. Treatment acronyms were given in Table 5.4.

5.3.6 Pasture Water use

5.3.6.1 Actual evapotranspiration

The closer fit of the observed and HYDRUS-simulated soil moisture contents, represented by lower mean daily biases and NRMSD values and higher NSE coefficients when compared with DairyMod (Table 5.15), resulted in a higher level of confidence being placed in the HYDRUS-simulated drainage and SMC. With HYDRUS, drainage and changes in the SMC (from 500-900 mm) could be simulated individually for all 16 treatment plots, unlike with DairyMod where they were simulated as an average for each treatment. The drainage and SMC simulated with HYDRUS were therefore used in the AET estimations (Section 5.2.7.4).

Annually, AET for the +I pastures exceeded (P<0.001) that from the -I pastures (Figure 5.18). In 2011/12 the AET from the +I pastures totalled 554 mm, compared with 487 mm from the -I pastures, a difference of 14%. In 2012/13, AET from the +I pastures (578 mm) was 36% greater than the -I pastures (425 mm). There were no differences in the AET from the +N and -N pastures in either year (0.076<P<0.410), totalling 521 mm in 2011/12 and 501 mm in 2012/13.
5.3.6.2 Water use efficiency

In 2011/12 the WUE of the pastures differed due to the effects of N fertiliser (P<0.001) (Figure 5.19). The +N pastures used water 33% more efficiently per kilogram of herbage mass produced than the -N pastures, producing 6.6 t DM/ha more for the same amount of water used (521 mm). The WUE of the +N pastures was 32.8±1.12 kg DM/ha/mm, equating to 11 kg DM/ha/mm more than the -N pastures (21.4±1.12 kg DM/ha/mm).

In 2012/13, the WUE of the -I pastures changed part way through the year due to the effects of water stress (Section 5.4.4). Split line regression analyses identified the date of the change to be the 7th and 8th November 2012 for the -I-N and -I+N pastures, respectively. On an annual basis, the main effects of nitrogen and irrigation were evident, although nitrogen was the dominant effect accounting for 61% of the SS\textsubscript{T} compared with 13% for irrigation. With 501 mm of water, the +N pastures produced 23.7±1.18 t DM/ha and the -N pastures produced 17.5±1.18 t DM/ha (P<0.001). Accordingly, the +N pastures used water 35% more efficiently per kilogram of herbage mass produced over the year than the -N pastures. Table 5.16 provides details of the WUE for each treatment, with treatment effects.
Figure 5.19 Accumulated total herbage yield against accumulated actual evapotranspiration (AET) of perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the periods 06/08/2011-06/08/2012 (2011/12) and 07/08/2012-31/07/2013 (2012/13). Treatments are +I+N (□), +I-N (■), -I+N (○) and -I-N (●). Dates when the water-use efficiency (slopes of lines) changed are indicated. Treatment acronyms were given in Table 5.4. Results differ to those given by Black and Murdoch (2013) due to the depth over which AET was calculated (i.e. 900 mm) and the inclusion of HYDRUS-simulated drainage and surface runoff in the AET calculations.

Table 5.16 Influence of irrigation and N fertiliser on the water-use efficiency of perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the periods 06/08/2011-06/08/2012 (2011/12) and 07/08/2012-31/07/2013 (2012/13). Treatment acronyms were given in Table 5.4.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2011/12</th>
<th>2012/13</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Annual</td>
<td>07-Aug-NoV</td>
</tr>
<tr>
<td>+I+N</td>
<td>33.6</td>
<td>-</td>
</tr>
<tr>
<td>+I-N</td>
<td>23.3</td>
<td>-</td>
</tr>
<tr>
<td>-I+N</td>
<td>32.1</td>
<td>41.9</td>
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<tr>
<td>-I-N</td>
<td>19.5</td>
<td>34.5</td>
</tr>
<tr>
<td>I</td>
<td>NS</td>
<td>-</td>
</tr>
<tr>
<td>N</td>
<td>&lt;0.001</td>
<td>0.037</td>
</tr>
<tr>
<td>I*N</td>
<td>NS</td>
<td>-</td>
</tr>
<tr>
<td>SEM(^2)</td>
<td>1.69</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Note 1: -I+N and -I-N pastures water use efficiency (WUE) values changed on 08/11/2012 and 07/11/2012, respectively, and were therefore analysed using a split-line regression model. All other treatments fitted to a simple linear regression model.

Note 2: Annual SEM values are those for I*N. The SEM of the 07 Aug-Nov relates to the effect of N. The SEM for the Nov-31 Jul is the pooled treatment SEM.
5.3.7 Potential evapotranspiration estimation

5.3.7.1 DairyMod, crop coefficient and Shuttleworth-Wallace modelled potential evapotranspiration using measured canopy data

DairyMod

DairyMod-simulated PETc to be within 36-70 mm (7-13%) of the measured AET, annually (Figure 5.20). NSE coefficients of 0.61-0.74 and NRMSD values of 0.48-0.63 were indicative of a reasonable match when AET was compared with the DMod-PETc estimations on a regrowth cycle basis (Table 5.17).

![Graph showing Accumulated AET, PETc (mm)](image)

Figure 5.20 Accumulated DairyMod-simulated potential crop evapotranspiration (solid lines) (DMod-PETc) and measured actual evapotranspiration (AET) for treatments +I+N (---□), +I-N (---■), -I+N (---○) and -I-N (---●) for perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the periods 06/08/2011-06/08/2012 and 07/08/2012-31/07/2013. Treatment acronyms were given in Table 5.4.
Table 5.17 Summary statistics comparing annual DairyMod-modelled, crop coefficient (Kc) based estimates, and maximum (SWW-PETmax) and HYDRUS adjusted (SWW-PETadj) Shuttleworth-Wallace estimates of potential crop evapotranspiration (PETc) of perennial ryegrass/white clover pastures at Lincoln University, Canterbury under treatments of irrigation (I) and nitrogen fertiliser (N). Results are for the periods 06/08/2011-06/08/2012 (2011/12) and 07/08/2012-31/07/2013 (2012/13). Treatment acronyms were given in Table 5.4. Crop coefficient time series used were the average lysimeter site time series developed from AET (with potential drainage) (Figure 4.19) and the mean lysimeter SWW-PETc-derived time series (Figure 4.18).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Summary statistic</th>
<th>DairyMod PETc</th>
<th>Lysimeter site averaged Kc time series</th>
<th>SWW-PETc-derived Kc time series</th>
<th>SWW-PETmax</th>
<th>SWW-PETadj</th>
</tr>
</thead>
<tbody>
<tr>
<td>+I+N</td>
<td>Total (mm)</td>
<td>508</td>
<td>524</td>
<td>614</td>
<td>659</td>
<td>610</td>
</tr>
<tr>
<td></td>
<td>Variation from total AET (mm)</td>
<td>-46</td>
<td>-58</td>
<td>60</td>
<td>77</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Variation from total AET (%)</td>
<td>-8</td>
<td>-10</td>
<td>11</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Mean daily bias (mm/d)</td>
<td>-0.13</td>
<td>-0.16</td>
<td>0.16</td>
<td>0.21</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>NSE</td>
<td>0.52</td>
<td>0.42</td>
<td>0.50</td>
<td>0.65</td>
<td>0.65</td>
</tr>
<tr>
<td></td>
<td>RMSD, NRMSD (mm,-)</td>
<td>24, 0.33</td>
<td>26, 0.37</td>
<td>24, 0.34</td>
<td>20, 0.29</td>
<td>17, 0.26</td>
</tr>
<tr>
<td>+I-N</td>
<td>Total (mm)</td>
<td>484</td>
<td>514</td>
<td>614</td>
<td>659</td>
<td>610</td>
</tr>
<tr>
<td></td>
<td>Variation from total AET (mm)</td>
<td>-70</td>
<td>-60</td>
<td>60</td>
<td>84</td>
<td>55</td>
</tr>
<tr>
<td></td>
<td>Variation from total AET (%)</td>
<td>-13</td>
<td>-10</td>
<td>11</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Mean daily bias (mm/d)</td>
<td>-0.19</td>
<td>-0.17</td>
<td>0.16</td>
<td>0.23</td>
<td>0.15</td>
</tr>
<tr>
<td></td>
<td>NSE</td>
<td>0.48</td>
<td>0.40</td>
<td>0.41</td>
<td>0.64</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>RMSD, NRMSD (mm,-)</td>
<td>27, 0.38</td>
<td>29, 0.41</td>
<td>26, 0.37</td>
<td>22, 0.31</td>
<td>19, 0.30</td>
</tr>
<tr>
<td>-I+N</td>
<td>Total (mm)</td>
<td>450</td>
<td>385</td>
<td>614</td>
<td>659</td>
<td>610</td>
</tr>
<tr>
<td></td>
<td>Variation from total AET (mm)</td>
<td>-36</td>
<td>-42</td>
<td>128</td>
<td>232</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td>Variation from total AET (%)</td>
<td>-7</td>
<td>-10</td>
<td>26</td>
<td>54</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Mean daily bias (mm/d)</td>
<td>-0.10</td>
<td>-0.12</td>
<td>0.35</td>
<td>0.65</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>NSE</td>
<td>0.63</td>
<td>-0.24</td>
<td>-0.46</td>
<td>-0.02</td>
<td>-0.02</td>
</tr>
<tr>
<td></td>
<td>RMSD, NRMSD (mm,-)</td>
<td>22, 0.39</td>
<td>41, 0.72</td>
<td>41, 0.73</td>
<td>37, 0.65</td>
<td>13, 0.26</td>
</tr>
<tr>
<td>-I-N</td>
<td>Total (mm)</td>
<td>431</td>
<td>382</td>
<td>614</td>
<td>659</td>
<td>610</td>
</tr>
<tr>
<td></td>
<td>Variation from total AET (mm)</td>
<td>-57.1</td>
<td>-40</td>
<td>126</td>
<td>236</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>Variation from total AET (%)</td>
<td>-11.7</td>
<td>-10</td>
<td>26</td>
<td>56</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>Mean daily bias (mm/d)</td>
<td>-0.16</td>
<td>-0.11</td>
<td>0.34</td>
<td>0.66</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>NSE</td>
<td>56</td>
<td>-0.19</td>
<td>-0.41</td>
<td>0.03</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>RMSD, NRMSD (mm,-)</td>
<td>24, 0.43</td>
<td>40, 0.71</td>
<td>41, 0.71</td>
<td>36, 0.64</td>
<td>14, 0.28</td>
</tr>
</tbody>
</table>
Crop coefficient time series

Crop coefficient time series developed in Chapter 4 from AET data (with estimated potential drainage) (Figure 4.19) and from mean lysimeter SWW-PET\(_c\) data (Figure 4.18), were found to predict water use to within a reasonable accuracy in the lysimeter experiment (Table 4.8). However, when either time series was applied to the current Lincoln experiment, both over-estimated the measured AET by 11-15% for the +I pastures and 26-56% for the -I pastures (Figure 5.21). NSE coefficients and NRMSD values were representative of a poor fit between the measured and predicted water use data for the -I pastures, but indicated a reasonable match for the +I pastures (Table 5.17). The differences, however, were largely attributable to observed soil moisture deficits across all the pastures. For example, the K\(_c\) estimated PET\(_c\) of the pastures was within 3-5% of the accumulated AET at the end of the Regrowths 4 and 11-13% at the end of Regrowth 11, around which time the soil moisture became limiting and therefore transpiration was reduced, as illustrated by the change in TAGR (Figure 5.7) and analysis of soil moisture (Section 5.3.5.1). After this time, the estimated PET\(_c\) deviated from AET. This has been discussed in Section 5.4.5.1.

![Figure 5.21](image-url) Accumulated measured actual evapotranspiration (AET) for treatments +I+N (◻), +I-N (■), -I+N (○) and -I-N (●) and potential crop evapotranspiration estimated using the average lysimeter site crop coefficient time series (K\(_c\)-PET\(_c\)) developed from AET (with potential drainage) (Figure 4.19) (—) and the mean lysimeter SWW-PET\(_c\)-derived time series (Figure 4.18) (----) in Chapter 4. Data presented are for perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the periods 06/08/2011-06/08/2012 and 07/08/2012-31/07/2013. Treatment acronyms were given in Table 5.4.

Shuttleworth-Wallace

Annual maximum SWW-derived PET\(_c\) (SWW-PET\(_{\text{max}}\)) was 581 mm in 2011/12 (P=0.264) across all treatments (Figure 5.22). In 2012/13 the annual SWW-PET\(_{\text{max}}\) estimations were affected by irrigation (P<0.001) and N fertiliser (P<0.001) and ranged between 611 and 613 mm for all pastures. However, differences of 2 mm on an annual basis are negligible. When compared with annual AET, SWW-PET\(_{\text{max}}\) estimations exceeded AET by 5-6% for the +I pastures and 19-45% for the -I pastures in 2011/12 and 2012/13 (Table 5.17). However, as illustrated by Figure 5.22, SWW-PET\(_{\text{max}}\) was estimated to be within
7% of the AET at the end of Regrowth 4 in 2011/12 and within 11% at the end of Regrowth 11 in 2012/13 of the -I pastures, after which point water became limiting and the AET fell below the potential.

When separated into soil evaporation and canopy transpiration (Table 5.18), there was a general pattern of higher (P<0.001) transpiration and less evaporation (P<0.001) from the +I and +N pastures. For example, in 2011/12, evaporation from the +I pastures was 72 mm compared with 80 mm from the -I pastures, and 70 mm from the +N pastures compared with 81 mm from the -N pastures. Transpiration from the +I and +N pastures was 510 and 511 mm, respectively, compared with 502 mm (-I) and 501 mm (-N). On an annual basis, however, these differences are still considered relatively small.

![Figure 5.22 Accumulated maximum Shuttleworth-Wallace (SWW) potential evapotranspiration (dashed lines: ---, ---) (SWW-PET_{max}), adjusted SWW potential evapotranspiration (solid lines: ―, ―) (SWW-PET_{adj}) and measured actual evapotranspiration (AET) for treatments +I+N (□), +I-N (■), -I+N (○) and -I-N (●) for perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the periods 06/08/2011-06/08/2012 and 07/08/2012-07/08/2013. SWW-PET_{max} values assume non-limiting supply of water to the plant while SWW-PET_{adj} values take into account periods where the soil moisture content of the soil restricted pasture transpiration. Treatment acronyms were given in Table 5.4.](image)

When the SWW-PET_{c} estimations were adjusted in HYDRUS to account for limiting soil moisture conditions (Section 5.2.7.5), the effects of irrigation on SWW PET_{c} estimations (SWW-PET_{adj}) became more pronounced (Figure 5.22). In both 2011/12 and 2012/13, SWW-PET_{adj} was affected by an I*N interaction. However, in both years irrigation accounted for more than 99% of the SS_{T}, and therefore the effects of nitrogen and the I*N interaction were minor in comparison, as illustrated in Table 5.18, and are not discussed further.

When compared with the measured AET (Figure 5.22), differences were within 3% annually. When SWW-PET_{adj} was compared with AET summed over each regrowth cycle, mean daily differences ranged from 0.01-1.83 mm and NSE values of 0.65-0.83 resulted (Table 5.17).
The daily SWW-PET_{adj} was also separated into soil evaporation and canopy transpiration (Table 5.18, Figure 5.23). Daily soil evaporation peaked following each grazing event, and then gradually reduced as the pasture developed and transpiration increased. During the months January-March of 2012 and mid-December-April/May of 2012/13, where large soil moisture deficits (to 900 mm soil depth) were estimated to be present (Figure 5.15), transpiration was low and at times ceased in the unirrigated plots. During these periods, evaporation of water from the soil surface was still evident following smaller rainfall events that wetted the soil surface but were insufficient to restore the soil profile moisture above the $\theta_L$. Within the irrigated plots, transpiration was maintained at the maximum rate, although evaporation was reduced from that in the SWW-PET_{max} estimations. Overall, the +I and +N pastures transpired up to 40% more (P<0.001) than the -I and -N pastures, but the +I and -N pastures lost up to 26% more water (P<0.001) via soil surface evaporation than the -I and +N pastures. In 2011/12 there were no significant differences in evaporation losses between the +I and -I pastures.

Table 5.18 Maximum and HYDRUS adjusted Shuttleworth-Wallace (SWW) potential evaporation (E), transpiration (T) and evapotranspiration (PET_{c}) estimates of perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the periods 06/08/2011-06/08/2012 (2011/12) and 07/08/2012-31/07/2013 (2012/13). Treatment acronyms were given in Table 5.4.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>2011/12</th>
<th>2012/13</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E</td>
<td>T</td>
</tr>
<tr>
<td>SWW-PET_{max}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>+I+N</td>
<td>67</td>
<td>514</td>
</tr>
<tr>
<td>+I-N</td>
<td>77</td>
<td>505</td>
</tr>
<tr>
<td>-I+N</td>
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<td>507</td>
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<td>85</td>
<td>496</td>
</tr>
<tr>
<td>I</td>
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<td>&lt;0.001</td>
</tr>
<tr>
<td>N</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>I*N</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>SEM_{I*N}</td>
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<td>1.4</td>
</tr>
<tr>
<td>SWW-PET_{adj}</td>
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<td></td>
</tr>
<tr>
<td>+I+N</td>
<td>57</td>
<td>514</td>
</tr>
<tr>
<td>+I-N</td>
<td>66</td>
<td>505</td>
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<td>-I-N</td>
<td>64</td>
<td>439</td>
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<tr>
<td>I</td>
<td>NS</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>N</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>I*N</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>SEM_{I*N}</td>
<td>1.27</td>
<td>1.21</td>
</tr>
</tbody>
</table>
5.3.7.2 Shuttleworth-Wallace modelled potential evapotranspiration using modelled canopy data

As a final step, daily outputs of leaf area index and height from the pasture growth model DairyMod were used as inputs to the SWW model to quantify differences in SWW evapotranspiration estimations using the simulated and observed canopy data (Section 5.3.4).

Where the soil moisture was assumed non-limiting, evapotranspiration (SWW-PET*max*) estimated using modelled canopy data was 1-2% (8-12 mm) less annually than that estimated using measured canopy data for each of the pastures (Table 5.19). When separated, the modelled canopy data led to annual evaporation predictions 30-75% (25-64 mm) higher and transpiration predictions 7-15% (36-73 mm) lower than the SWW-PET*max* predictions based on measured canopy data.

The differences were similar when SWW-PET*adj* estimations determined with measured and simulated canopy LAI and height were compared (Table 5.19). Annually, SWW-PET*adj* estimated using modelled canopy LAI and height data were <1-4% (1-20 mm) less than that estimated using measured canopy data. Annual evaporation predictions using modelled canopy data were 23-48% (13-31 mm) greater.
than when measured canopy data were used, and transpiration predictions were 4-10% (15-51 mm) less (Table 5.19).

Statistical comparison of the evapotranspiration estimations on a per rotation basis indicated that whether measured or modelled pasture growth data were used to estimate SWW-PET$_c$ (maximum or adjusted), the results were comparable with NSE values >0.99. When SWW-PET$_{adj}$ calculated with modelled canopy data were compared with measured AET, NSE values decreased by 0.01 in the -I+N pastures from those determined from measured canopy data (Table 5.17), but increased by 0.03 in the +I pastures. The NSE coefficients were 0.68, 0.69, 0.82 and 0.83 for the +I+N, +I-N, -I+N and -I-N pastures, respectively. The NRMSD values across all treatments were reasonably low at 0.27-0.29.

Annually, SWW-PET$_{adj}$ with modelled canopy data was within 2% of the annual AET, similar to the 0-2% of the SWW-PET$_{adj}$ determined using measured canopy LAI and height data (Table 5.17).

Table 5.19  Summary of annual maximum (SWW-PET$_{max}$) and adjusted (SWW-PET$_{adj}$) Shuttleworth-Wallace potential evaporation (E), transpiration (T), and evapotranspiration (PET$_c$), of a modelled perennial ryegrass/white clover pasture at Lincoln University, Canterbury under treatments of irrigation and N fertiliser. Results are for the periods 06/08/2011-06/08/2012 (2011/12) and 07/08/2012-31/07/2013 (2012/13). Values in brackets are the percentage differences from SWW-PET$_c$ maximum and water stress adjusted values determined using measured canopy LAI and height data (Table 5.17).
Figure 5.24  Accumulated adjusted Shuttleworth-Wallace (SWW) potential evapotranspiration (SWW-PET\textsubscript{adj}) using modelled (dashed line) and measured (solid line) canopy leaf area and height data, and measured actual evapotranspiration (AET) for treatments +I+N (□), +I-N (■), -I+N (○) and -I-N (●) for perennial ryegrass/white clover pastures at Lincoln University, Canterbury, for the periods 06/08/2011-06/08/2012 and 07/08/2012-31/07/2013. Treatment acronyms were given in Table 5.4.
5.4 Discussion

This chapter had a main objective of validating models that simulate pasture growth (DairyMod) and/or soil water flow through the soil (DairyMod and HYDRUS-1D) and estimate PETc (DairyMod, Ke time series and SWW). This chapter also focused on quantifying the effects of nitrogen and water availability on evapotranspiration estimations. These were achieved using a previously published data set of water use and pasture growth data from a range of perennial ryegrass/white clover pastures grown on one site at Lincoln University, Canterbury.

5.4.1 Agronomic performance of perennial ryegrass/white clover pasture

Treatments of N fertiliser and irrigation on the perennial ryegrass/white clover pastures at Lincoln University provided a wide range of pasture performance within a controlled field experiment that could be used for the validation of models used to simulate pasture growth, soil water flow and PETc. This discussion initially examines pasture performance in relation to the effects of irrigation and nitrogen, and compares pasture growth with that observed in the lysimeter experiment in Chapter 3, against which each of the models were calibrated.

5.4.1.1 Herbage dry matter production

Over the two-year experiment, variations in water and nitrogen fertiliser conditions across the four treatments led to a wide range in pasture yields (Figure 5.6).

The maximum yield achieved by the pastures was 21 t DM/ha in 2011/12 with treatments of irrigation and nitrogen. Without irrigation, herbage yields reduced to \(~85\%\) of the maximum, but without nitrogen, yields reduced to \(~66\%\). These results highlighted nitrogen to be the most limiting factor, which is supported by the literature (Section 2.3.2.4). Mills et al. (2006), for example, reported a greater than 50% reduction in cocksfoot biomass production under nitrogen-deficient conditions compared with a reduction of \(~28\%\) when water was the limiting factor.

Observed herbage yields across all treatments in 2012/13 were lower than those for 2011/12. This was largely in response to the lower than average irrigation season rainfall, and 5% higher than average PETc demand (Table 5.3), increasing the soil moisture deficits and therefore the effects of water stress. Accordingly, irrigation became the apparent dominant influence on growth, whereby the +I-N pasture production was 5% greater than the -I+N pastures. This is because water is required for the uptake of nutrients from the soil, therefore even with non-limiting nitrogen, herbage accumulation will be restricted according to the availability of water to the pasture. This was identified by Mills (2007), whereby non-limiting N, dryland cocksfoot pasture production fell below that of an irrigated cocksfoot with limiting nitrogen during periods of water stress.
Overall, however, the observed pasture growth was within the range of 5-25 t DM/ha/y reported throughout the literature for pasture in Canterbury under varied nitrogen and irrigation managements (Fasi et al., 2008; Hayman, 1985; Kemp et al., 1999; Martin et al., 2006; McBride, 1994; Minneé et al., 2010), and was comparable to the herbage yields observed at LDF in the irrigated lysimeter experiment where nitrogen was limiting (Figure 3.11).

5.4.1.2 Temperature adjusted pasture growth
Thermal time was used to quantify pasture growth without the influence of temperature variation. Herbage mass production per unit of thermal time from the -N pastures was 66-74% that of the +N pastures (Table 5.11). This is consistent with previous findings for cocksfoot pasture in Canterbury for which the TAGR of unfertilised pastures was 3.2 kg DM/ha/°Cd, 56% less than those fertilised with nitrogen at 7.2 kg DM/ha/°Cd (Mills et al., 2006). The results also compare with those of the lysimeter experiment (Section 3.3.3) where the nitrogen-limited ryegrass pastures grew at a TAGR of 3.9 kg DM/ha/°Cd. Irrigation also affected TAGRs, whereby the +I pastures grew on average 20-30% faster per unit of thermal time than the -I pastures due to the effects of water stress.

The effects of water stress, however, were evident across all pastures, whereby changes in the TAGR in Figure 5.7 largely coincided with reductions in the available soil water to or near the critical limiting soil moisture content of 24% (Figure 5.15). Tonmukayakul (2009) found that TAGRs were highest in spring when soil moisture contents were high but reduced in summer due to the effects of water stress on canopy extension, leaf size and tiller population of the pasture. However, as indicated in Section 5.3.5.1, the change in the TAGR was delayed compared with the timing at which the measured 0-500 mm soil moisture fell below the critical level by up to nearly a month. This verified the DairyMod model results that indicated abstraction was occurring from below the measured 500 mm depth, and may have been from a depth of down to 900 mm (Section 5.2.6.1).

5.4.1.3 Herbage nitrogen
The measured herbage nitrogen fluctuated throughout the experiment. At the measured concentrations, photosynthetic efficiency was estimated to be on average ~78% for the +I and +N pastures and ~73% for the -I and -N pastures (Peri, 2002). In each of the pastures, however, the nitrogen concentration fell below the critical concentration of 2.6%, below which photosynthesis is severely constrained (Peri et al., 2002b), and below an NNI of 0.8 (Section 2.3.2.4). This was expected for the -N pastures. However, despite luxury N applications to the +N pastures (Figure 5.8), N concentrations and NNI values as low as 1.8% and 0.5, respectively, were observed. This, once again, occurred during periods of water stress, namely from November 2011-March 2012 and during November 2012 for the +I+N pastures, and from ~October-May 2011/12 and ~October to March 2012/13 for the -I+N pastures (Figure 5.13), and can be explained. Plant nutrients such as nitrogen are
often concentrated near the soil surface (Garwood & Sinclair, 1979; Garwood & Williams, 1967). However, once the upper soil horizons become dry due to insufficient inputs of irrigation or rainfall, the nitrogen in these layers becomes unavailable to the plant, and can lead to nitrogen deficiency, even if sufficient water is available to the pasture lower in the profile (Section 2.3.2.2). This also provides reasoning for the observation of critical nitrogen concentrations for longer periods in the -N pastures compared with the +N pastures (Figure 5.8).

### 5.4.2 Use of DairyMod for the simulation of pasture growth

Calibration of DairyMod at LDF confirmed its potential for use in simulating pasture growth under a grazed, irrigated commercial dairy farm environment (Section 3.3.8). However, limitations within the model regarding its inability to adapt leaf area extension to changes in nitrogen supply were identified (Sections 3.4.1.7 and 4.4.2.1). In this chapter, the objective was to validate the calibrated DairyMod model against measured annual and regrowth-based herbage mass of perennial ryegrass/white clover pastures at Lincoln University under different irrigation and N fertiliser management strategies (Section 5.3.4). However, the calibrated model over- and under-estimated annual herbage accumulation by up to 62%, and the modelled yields did not reflect variations in N supply, with little differences (<0.6 t DM/ha/y) in the simulated herbage of the +N and -N pastures (Figure 5.9a-b). This was a result of the low high temperature stress values required in the calibrated model to achieve a reasonable match between the observed an simulated lysimeter data in Chapter 3. The ascribed temperature values, however, meant that in the Lincoln experiment temperature become more limiting than nitrogen, and therefore the model did not respond to changes in the level of nitrogen fertiliser.

To improve the modelled annual herbage yield predictions to within 4-18% of the observed, the post-grazing herbage residuals for the first regrowth of each year had to be increased to 2-3 t DM/ha to correct an initial offset in the predictions, and adjustments to the temperature functions were required. While residuals of 2-3 t DM/ha are high (Section 2.3.2.5) the WUE analyses in Figure 5.19 indicate that initial residuals of 2.2 t DM/ha were possible, based on the y-axis intercepts.

While changes to the temperature functions allowed for a close fit between the observed and simulated accumulated herbage production to be achieved, the fit of the observed and simulated canopy LAI and height data was poor, as was the prediction of herbage nitrogen by DairyMod. For example, the leaf area index of the simulated pastures was on average 0.5 m²/m² (or 16%) lower than the observed, but biases of 0.34-1.12% in herbage N persisted, with differences of up to 2% from the observed herbage nitrogen content. Accordingly, despite the apparent availability of nitrogen within DairyMod to the pasture (Figure 5.12), the model failed to correctly simulate leaf development in response to nitrogen. (Section 2.3.2.4). However, the simulated pasture height was on average 36 mm
(or 27%) higher than the observed (Figure 5.10), suggesting that reduced tiller development may have been responsible for the differences in the observed and simulated LAI. A positive relationship exists between nitrogen application and increased tiller and leaf population and weight (Akmal & Janssens, 2004; O’Brien, 2010; Wilman & Fisher, 1996; Wilman et al., 1976) (Section 2.3.2.4). For example, the tiller population of perennial ryegrass increased by 33% and tiller weight by 26% with increases in nitrogen application from 28 kg/ha to 198 kg/ha (Wilman et al., 1976). This highlights an area of possible improvement within DairyMod.

Overall, however, the results were within the range of those observed in similar studies, including Cullen et al. (2008), who reported annual percentage differences of 0.4-30.3% between measured and modelled data, and White et al. (2008) (Section 2.3.2.6). As in the current experiment, to achieve these results, adjustments to the temperature functions were required. However, while Cullen et al. (2008) indicated that the temperature stress functions were activated, the actual temperature settings applied were not specified.

5.4.3 Simulation of soil moisture, profile drainage and surface redistribution of water

Both DairyMod and HYDRUS were used to simulate soil water flow through the 500 mm soil profile at Iversen Field, Lincoln University. As in the lysimeter experiment (Chapter 4), HYDRUS was found overall to be the superior model based on the ability of HYDRUS to achieve a closer match between the observed and simulated soil moisture in the upper 500 mm soil profile (Section 5.3.5.2).

In the Lincoln experiment, despite a close fit between the observed and simulated herbage yield, the model underestimated LAI but overestimated the herbage nitrogen content. This suggests that the relationship between N supply and leaf area discussed by Grindlay (1997) is not sufficiently accounted for within the model. This had a flow-on effect to other aspects of the model, whereby the potential evapotranspiration of the pasture was under-estimated, which followed on to an under-estimation of the soil moisture deficits achieved, and therefore the simulated drainage was greater than that simulated using HYDRUS. As a result, the remainder of the discussion in this section is focused on the performance of HYDRUS in the simulation of soil water flow.

5.4.3.1 Performance of HYDRUS in the simulation of soil moisture

Soil moisture is difficult to model due to soil’s inherent variability (Porteous et al., 1994). Despite this, a strong fit between the observed and simulated soil moisture contents across all treatments was achieved with HYDRUS with NSE values of 0.52-0.86 and low NRMSD values of 0.09-0.11 (Table 5.15). The mean daily bias of up to 1% (9 mm over 900 mm profile) was comparable to the 0.8-3.4% (1-24 mm over 500 mm profile) biases observed in the lysimeter experiment (Table 4.7). These results compare with optimised model performance reported by Wöhling and Vrugt (2007) and Zhou et al.
(2012), whereby NSE coefficients up to 0.87 were achieved when observed and simulated soil moisture data were compared.

Adjustments made to the calibrated model h4 value (Table 4.3) and soil hydraulic property n values determined for the Wakanui soil at the Lincoln site (Table 5.9) largely overcame shortcomings in the calibrated model when it was applied to the -I pastures at Lincoln. This was because the simulated soil moisture was prevented from drying out to the same extent as what was observed.

Changing the value of h4 in the calibrated model had little effect on the overall soil moisture predictions in the +I pastures. This was probably because the soil moisture was generally maintained near field capacity (Figure 5.13), and therefore there was no need within the model to account for abstraction during larger soil moisture deficits. Similarly, with the calibrated model at LDF, whether a value of -800 kPa or -1500 kPa was used, there were no differences in the model performance (Table 4.3). However, for the -I pastures in the Lincoln experiment, large soil moisture deficits occurred from 17 December 2012 to 21 January 2013 and from 11 February to 21 March 2013. At a value of -800 kPa for h4, abstraction during these periods was not adequately accounted for within the model, but reducing h4 to -1,500 kPa largely resolved this. A value of -1,500 kPa is widely accepted as being representative of the lower limit of plant water abstraction (Section 2.3.2.2), and therefore should be used in the calibrated model.

The need to increase the default value of n (Table 5.9) by 5% in the -I pastures compared with the 1% determined in the site specific parameter testing (Table 5.10) reflected spatial variability in the soil. The soil hydraulic property data were based on measurements 1.4 km from the experiment site, and therefore may not have been directly representative of the conditions at the site. If soil hydraulic measurements had been taken from the experiment site, the need for parameter adjustment would have probably been avoided. Despite this, close agreement between the observed and simulated soil moisture data was achieved, as illustrated by Figure 5.15.

5.4.3.2 Simulated profile drainage and surface run-off of water

Differences in the HYDRUS estimated drainage between the +I and -I pastures, while statistically different (P<0.001), were in absolute terms small (i.e. <5 mm) up until the last or second to last regrowth cycles of each year (Figure 5.16). When rain fell at the end of each irrigation season, the +I pastures had less capacity to store the water due to maintenance of a higher soil moisture status compared with the -I pastures. This subsequently led to ~40 mm more (P<0.001) modelled drainage from the +I pastures during Regrowths 8 and 16. These results therefore suggest that the drainage under irrigation could have been reduced if less irrigation water had been applied towards the end of the irrigation season, through increased available water storage capacity of the soil. This has been explored further in Chapter 6. Multiple high rainfall events (>25-30 mm/d) in August 2012 and June
2013 (Figure 5.2) led to the increase in modelled drainage for 2012/13 (360-411 mm) compared with 2011/12 (148-182 mm) (Figure 5.16).

While no direct comparisons of drainage as a percentage of rainfall and irrigation inputs from a Wakanui silt loam were evident in the literature, the HYDRUS-simulated drainage under irrigated (34%) and dryland (36%) conditions was comparable to the 11-39% observed in the lysimeter experiment (Section 4.4.1). It was also within the range reported in the literature for other soils in Canterbury (Section 2.3.3).

In addition to drainage, HYDRUS also estimated the potential run-off of water from the surface of the pastures (Figure 5.17), although the amount predicted was negligible (<0.1 mm/y). Infiltration rates of up to ~400 mm/h have been reported in the literature for a dry Wakanui silt loam under permanent pasture, reducing to a steady state of ~16 mm/h (Gibbs, 1986; Hermawan, 1990; Lance, 1987) (Section 2.3.3.2). While irrigation water was applied at rates of up to 25 mm/h (Figure 5.1), in excess of the steady state infiltration rate, the timing of irrigation probably limited the potential for runoff. The pastures were irrigated when sufficient soil moisture deficits had developed within the profile, and suggest that infiltration into the soil at these times was at least equal to the rate of irrigation application. The maximum recorded rainfall intensity of 52 mm/h occurred on 01/05/2013 when 20 mm of rain fell over an 80 minute period (Figure 5.1). At this time, however, the soil moisture deficit in the upper 500 mm soil profile was between 35 and 65 mm across the pastures, and therefore infiltration into the soil was likely sufficient to account for the intensity of the rainfall.

5.4.4 Effects of nitrogen fertiliser and irrigation on actual water use and water use efficiency

In 2011/12 and 2012/13, nitrogen had no effect on AET (0.076<P<0.410) (Figure 5.18). Essentially, the AET of the pastures was similar, regardless of whether or not N fertiliser was applied as, despite the production of 6.6 t DM/ha/y more by the +N pastures, the water use of the +N and -N pastures was the same (474 mm) (P=0.200). However, while water use of pasture is not dependent on herbage yield, the herbage yield influences the WUE of the pasture. Accordingly, a maximum annual WUE of ~33 kg DM/ha/mm was quantified from the herbage yield and AET data of the +N pastures in 2011/12, which exceeded (P<0.001) the WUE of the -N pastures of ~21 kg DM/ha/mm by 57%. These results are supported by the findings of Mills et al. (2009) for a cocksfoot pasture and Black and Murdoch (2013) for ryegrass (Section 2.3.2.4).

As discussed (Section 4.4.3), N limiting conditions can reduce the transpiration potential (Johns & Lazenby, 1973). However, this can be offset by increases in soil evaporation, which limits the effect of N fertiliser on AET (Van Keulen et al., 1989). Furthermore, once full canopy cover is achieved, the canopy will transpire at the potential rate, again diminishing the effects of N on AET. In contrast,
irrigation increased annual AET in the +I pastures above that from the -I pastures by 14-36%, which compares with the findings by Mills (2007) who reported dryland cocksfoot pasture water use was 33-50% lower than that grown without water limitations to growth.

While the Lincoln experiment data is based on that collected and reported by Black and Murdoch (2013) (Section 2.3.2.4), the calculated AET and WUE values differ (Table 5.16). This is because in their estimations, Black and Murdoch (2013) assumed a rooting depth of 500 mm and did not account for losses of water via drainage or surface runoff. In the current experiment, a potential rooting depth of up to 900 mm was identified (Section 5.2.6.1), and drainage below this depth was estimated to be 148-411 mm/y across the four treatments (Figure 5.16). Differences in the AET calculations increased the annual calculated WUE in 2011/12 by 2-6 kg DM/ha/mm but decreased the WUE in 2012/13 by 1-3 kg DM/ha/mm.

As with 2011/12, the maximum WUE of the +N pastures (~24 kg DM/ha/mm) exceeded (P<0.001) that of the -N pastures (~17 kg DM/ha/mm) in 2012/13. However, within the unirrigated pastures there was a distinct change in the WUE mid-November 2012 due to the effects of water stress. Around the time that the WUE reduced, the SMC reached the critical 24% and continued to dry to 12% (Figure 5.15). Water stress limits nitrogen uptake by the pasture from the soil which in turn reduces dry matter production and also the WUE (Garwood & Sinclair, 1979; Garwood & Williams, 1967; Mills et al., 2009). This was reflected in the observed nitrogen concentrations (Figure 5.8), as discussed in Section 5.4.1.3.

When compared with the WUE determined for the lysimeter-grown ryegrass pastures in Section 4.3.3.2, the WUE of all pastures in the Lincoln experiment were higher. This was due to the nitrogen limiting conditions of the lysimeter pastures compared with the +N pastures in the Lincoln experiment, and also the higher total amounts and proportion of evaporative losses from the lysimeters. For example, evaporation was estimated to be ~120 mm of the total 615 mm of AET (i.e. 20%) at LDF (Table 4.10), compared with 48-68 mm of the 424-588 mm of water used per year (i.e. 10-13%) in the Lincoln experiment (Table 5.18). This was in response to the higher frequency of irrigation (Figure 3.2) and maintenance of a higher soil moisture status (Figure 4.4) in the lysimeters, particularly at LDF and TSD, and smaller LAIs for the lysimeter pastures (Table 3.12) compared with those in the Lincoln experiment (Table 5.14).

5.4.5 Potential crop evapotranspiration

Daily potential evapotranspiration from the ±irrigation and ±nitrogen treatment plots estimated using the crop coefficient time series developed in the lysimeter experiment (Chapter 4) and the Shuttleworth-Wallace PETc model yielded comparable results, when water was not limiting.

Due to the limitations identified in DairyMod in regard to its ability to accurately simulate leaf extension in response to nitrogen supply (Section 5.4.2), the model under-estimated the potential
evapotranspiration. This subsequently led to under- and over-estimations of drainage and soil moisture, respectively. Accordingly, further discussion of the DairyMod PET<sub>c</sub> predictions has been excluded from the following sections.

5.4.5.1 **Crop coefficient time series**

The application of the monthly averaged K<sub>c</sub> time series developed in the lysimeter experiment from AET (Figure 4.19) and the time series from mean lysimeter daily SWW-PET<sub>c</sub> data (Figure 4.18), led to over-estimations of water use from all treatments at the Lincoln site by 11-54% (Table 5.17). These results indicated that neither time series was appropriate for estimating water use at the Lincoln site. The over-estimations were in response to limiting soil water conditions because the time series’ had been developed under non-limiting conditions. Accordingly, the closer fit of the estimated PET<sub>c</sub> of the +I pastures (Figure 5.21) was expected as they maintained higher soil water contents over the experiment, reducing the effect of water stress. However, differences were reduced to 5-13% across all treatments during the irrigation season months where the soil moisture was not limiting.

Outside of the irrigation season months, where water stress had been alleviated, it was also expected that differences between the K<sub>c</sub>-PET<sub>c</sub> estimates and the observed AET would be small. However, during each of Regrowths 8 and 16, for example, the AET was calculated to be 0-16 mm whereas K<sub>c</sub>-PET<sub>c</sub> was estimated at 26-44 mm by the two K<sub>c</sub> time series. This indicates that the K<sub>c</sub> values determined for months outside of the irrigation season may not be representative on a regional scale. However, this is relatively unimportant in practice because water use estimations are generally required during the irrigation season only.

Inter-annual differences in the predictions, whereby in 2011/12 the K<sub>c</sub> time series estimated water use to within 11-26% of AET compared with 13-54% in 2012/13, was a direct response to the greater atmospheric evapotranspiration demand (Section 5.2.3.1) resulting in the development of greater actual soil moisture deficits for more of the growing season in 2012/13 (Figure 5.13).

In light of the results, the use of the developed K<sub>c</sub> time series should be limited to the estimation of water use from fully irrigated dairy pastures during the irrigation season months, and should only be used for longer-term (i.e. irrigation season based) estimates.

5.4.5.2 **Shuttleworth-Wallace**

As with other standard PET<sub>c</sub> models, SWW assumes water is freely available to the plant (Section 2.4.2.4), although evaporation is limited within the model according to soil moisture availability at the surface. While the intention of the experiment was to maintain the soil moisture of the +I pastures above the critical level of 24%, the amount of irrigation applied was insufficient to fully achieve this, as reflected by the change in temperature adjusted growth rates (Figure 5.7) and the estimations of PET<sub>c</sub> using the K<sub>c</sub> time series (Figure 5.21). For periods during 2011/12 and 2012/13 the actual soil
moisture deficit exceeded the critical level (Figure 5.15), and consequently AET fell below the maximum PETc (Figure 5.22). Yet, regardless of periods of water stress, SWW predicted actual pasture water use with and without N fertiliser to within 5-6% of AET for the +I pastures. For the -I pastures, SWW over-estimated water use by up to 45% (Table 5.17). HYDRUS was therefore used to account for the effect of water stress in the SWW PETc calculations (Section 5.2.7.5).

Within HYDRUS, the actual transpiration and evaporation rates are restricted by the prevailing soil moisture conditions (Section 2.3.3.4). Where the soil moisture conditions allow, the actual transpiration and evaporation rates are maintained equal to the potential rates, i.e. SWW-PETmax. When the soil dries below the critical levels (Table 5.10), plant water uptake and evaporation reduce below the potential, as determined by Equations 2.29 and 2.27, respectively. When adjusted for limiting soil water conditions, the performance of the SWW model improved, with annual estimations of SWW-PETadj within 2% of the AET across all four treatment pastures (Table 5.17), similar to the results of the lysimeter experiment (Table 4.9). Statistical comparison of SWW-PETadj estimations with AET on a regrowth cycle basis also indicated a strong fit with NSE values of 0.74-0.82. Accordingly, the SWW model was confirmed as an acceptable predictor of evapotranspiration irrespective of pasture performance, when water stress was absent or if sufficiently accounted for. The estimation of PETc over longer than weekly periods was also found to be preferable. However, estimations over shorter periods (for example one week) were reasonable with NSE values of 0.47-0.60.

However, it must be highlighted that the HYDRUS adjusted SWW estimations are not entirely independent, and therefore the close fit of SWW-PETc to AET needs to be interpreted with caution. In the Lincoln experiment, HYDRUS simulated surface runoff, drainage below 900 mm and changes in the soil moisture between 500-900 mm were used in the estimation of AET with Equation 4.2. Accordingly, the only potential for difference between AET and SWW-PETadj was in the change in SMC from 0-500 mm, which was measured on-site. This inevitably led to the close fit of the data. Nevertheless, in the lysimeter experiments where water stress was not evident and AET was calculated independent of the SWW estimates, the fit of SWW-PETc with AET was strong and when SWW-PETc was input into HYDRUS, the model did not limit the SWW estimations, which is representative of what occurred in practice.

**Soil surface evaporation and canopy transpiration partitioning**

The results in Table 5.18 provided insight into the partitioning between evaporation and transpiration under different pasture managements.

The greater amounts of evaporation and transpiration under irrigation can be explained. Under irrigation the soil surface is wetted more frequently, allowing for greater evaporative losses relative to a rain-fed pasture (Wright, 1982). Irrigation, where sufficient, also allows the canopy to develop without water limitations. When the canopy comes under stress, as occurred in the -I pastures for
extended periods, turgor pressure declines and cell expansion is reduced, leading to the formation of smaller leaves. When the leaf area is below 95%, reductions in photosynthesis and transpiration result (Brougham, 1958; Hsiao, 1973; Johns, 1978).

While total SWW-PET adj was relatively unaffected by N fertilisation, the amounts separately transpired by the canopy and evaporated from the soil surface were. As discussed in Section 5.4.4, differences in evaporation and transpiration under varying N fertilisation occur due to the reduced leaf area of a nitrogen-deficient pasture compared with a well-fertilised pasture. This can lead to reductions in transpiration but can increase evaporation of water from the soil surface due to less radiation being intercepted by the canopy (Johns & Lazenby, 1973; Mills et al., 2009; Van Keulen et al., 1989). Table 5.14 and Section 5.3.4 provide a summary of the LAI and height data estimated for each of the pasture treatments. While the range in LAI values of the +I (0.9-8.7) and -I (0.9-8.7) pastures were the same, the daily LAI values of the +I pastures were on average 10% greater than those of the -I pastures. Similarly, the LAI values of the +N pastures were on average 17% greater than the -N pastures. This compares with findings by O’Brien (2010) whereby the leaf extension rate (mm/°Cd) was 2-28% greater for a fertilised perennial ryegrass pasture compared with an unfertilised pasture. Overall, however, the effects of nitrogen were relatively small on PETc estimations as well as the partitioning of PETc into evaporation and transpiration. This is not surprising as such effects only occur in the earlier stages of growth, prior to full cover being achieved. Once full cover is achieved, transpiration will occur at the potential rate, and evaporation is of less significance due to greater interception of radiation by the canopy.

5.4.6 Estimation of Shuttleworth-Wallace potential evapotranspiration using simulated canopy leaf area and height.

Over the experimental period, the effect of using modelled canopy data in the estimation of SWW-PET adj was small (1-4% per annum) (Figure 5.24, Table 5.19) when compared with annual estimates using canopy LAI and height derived from RPM measurements (Section 5.2.7.5). When compared with annual AET, differences of 2% were identified. This compares with the 1% difference at LDF when the observed and simulated canopy data were used in the estimation of SWW-PETc and difference of 2% when the SWW-PETc, with modelled canopy data, was compared with AET (Table 4.10). Accordingly, irrespective of the use of measured or modelled canopy data, where for the modelled data the local climate, soil, pasture species, and grazing, fertilisation and irrigation management strategies are described in the pasture growth model DairyMod, the SWW model was able to predict evapotranspiration to within an accuracy of ~3%.

As at LDF, however, the use of modelled canopy data in the estimation of SWW-PETc led to differences in the evaporation and transpiration components for PETc compared with when measured canopy data were used (Table 5.19). Annual evaporation estimates using simulated canopy LAI and height differed
from estimates using measured canopy data by 23-48% (13-29 mm), whereas transpiration varied by a lesser 4-10% (15-51 mm). The smaller mean daily LAI values of the simulated pastures compared with the measured pasture data (Table 5.14, Figure 5.11), led to less radiation interception by the canopy, reducing the potential transpiration but increased the proportion of the soil surface exposed, thereby increasing the potential for evaporation of water from the soil surface (Brougham, 1958; Hsiao, 1973; Johns, 1978). This was emphasised by the data whereby the percentage differences in the estimated evaporation using the measured and modelled canopy data were greatest for the +I+N pastures (average of 38%) (Table 5.19), which also had the largest simulated mean daily LAI bias of 0.6 (Table 5.14).
5.5 Conclusions

The focus of Chapter 5 was to validate models used to predict pasture growth, soil water flow and/or evapotranspiration from a range of field-grown perennial ryegrass-based pastures on a single site in Canterbury, thereby achieving Objective 7. This was necessary to test the hypothesis of the research by providing a range of pastures against which the accuracy of the developed \( K_c \) time series and other models used in the estimation of evapotranspiration could be evaluated. A number of conclusions can be drawn from the results of Chapter 5.

As expected, the performance of perennial ryegrass/white clover pastures, when subjected to treatment combinations of ±irrigation and ±nitrogen fertiliser, differed for annual herbage yields and growth rates. Because of this, the effectiveness of existing models for estimating PET\(_c\), and simulating pasture growth and variably saturated water flow could be validated across a wide range of pasture performance that exists across dairy farms in Canterbury.

DairyMod was effective at simulating herbage accumulation in the Lincoln experiment once the values attributed to the high temperature stress parameters in the calibrated model were increased. This was necessary to prevent temperature from limiting the potential for a nitrogen response within the model. However, the model was unable to correctly simulate canopy LAI, height and nitrogen content. This was attributed to a failure within the model to fully account for the mechanistic relationship between leaf extension and nitrogen. Consequently, the model under-estimated evapotranspiration from the pasture, which led to an over-estimation of soil moisture in the upper 500 mm and drainage below 900 mm when compared with the HYDRUS simulations. However, it is expected that if the model had accurately simulated leaf development, evapotranspiration, soil moisture and drainage would have most certainly improved. This provides a potential area for improvement within the model.

In comparison, HYDRUS successfully simulated soil moisture to 500 mm for each of the treatment soil profiles, which gave confidence in its ability to simulate drainage of water from the root zone. This was supported by the findings in Chapter 4, whereby HYDRUS effectively simulated lysimeter drainage. However, having site-specific measurements of the soil hydraulic properties for inputs to the model is desirable.

When soil moisture was limiting, the \( K_c \) time series and SWW model over-estimated PET\(_c\). However, when limiting soil moisture conditions were accounted for, or where the irrigation was sufficient, the models both provided an effective method for estimating PET\(_c\) for perennial ryegrass/white clover pastures in Canterbury, irrespective of N fertiliser application. However, the \( K_c \) time series was inappropriate for estimating water use outside of the irrigation season months and due to spatial variability in AET, so should be restricted to longer-term (i.e. irrigation season) estimates. Overall, SWW was found to be the superior method for estimating PET\(_c\), with estimates of water use to within
an accuracy of 3% annually. In the Lincoln experiment, as drainage was not measured and soil moisture was only measured to 500 mm, the use of simulated drainage and soil moisture changes below 500 mm in the AET calculations meant that the SWW predictions, when adjusted for moisture stress, were not independent. Despite this, the SWW model, prior to water stress, was able to independently predict evapotranspiration to a high accuracy. This, coupled with the success of SWW in Chapter 4 when tested against three independently determined water use data sets, is considered to provide sufficient justification for its use and confirms its ability to accurately predict water use for grazed pasture above other commonly applied models, including Penman-Monteith.

Using DairyMod-simulated LAI and height in SWW-PETc predictions emphasised the importance of using accurate canopy data. While overall there was little difference in the PETc predictions when simulated or observed canopy data were used, errors in the simulated canopy data led to differences in the soil surface evaporation and transpiration components. This again stems from the limitation within DairyMod to accurately simulate leaf extension, often resulting in higher levels of evaporation than what occurred due to greater ground surface exposure. Despite this, where measured data are not available, DairyMod-simulated canopy data can be used to obtain reasonable values of total PETc.

Drainage from the +I pastures exceeded that from the -I pastures. However, the greatest differences occurred during the shoulder months of the irrigation seasons. If less irrigation had been applied towards the end of the season to allow for greater storage of autumn and winter rainfall, much of the differences in drainage between the +I and -I pastures could have been avoided. This highlights an area where irrigation management can be improved, which has been explored in Chapter 6.
Chapter 6
Scenario Testing

6.1 Introduction

Chapters 3 to 5 confirmed the hypothesis that the spatial variability in evapotranspiration from irrigated, grazed perennial ryegrass pasture across the Canterbury Plains precludes the use of a single \( K_c \) time series for accurately modelling evapotranspiration over short time periods, although the time series can be used for irrigation season based estimates (i.e. September-April) where water is not limiting to the pasture. The Shuttleworth-Wallace evapotranspiration model can, however, be used to predict \( PET_c \) over short time periods, when pasture variables of leaf area and height are known or have been simulated.

Using the models assessed in Chapters 3 to 5, including DairyMod for simulating pasture growth, HYDRUS for simulating soil water flow and the Shuttleworth-Wallace evapotranspiration model, this chapter investigates irrigation efficiency of pasture under a commercial dairy farming operation to minimise non-productive water losses and maximise on-farm productivity. This addresses Objective 8 (Section 1.4). To achieve this, a range of irrigation scheduling scenarios have been tested to address questions 1-4 (below) for each of the three commercial dairy farms: LDF, TSD and PF. The nine-month period from 1 July 2014 to 31 March 2015 was selected for the scenario testing, as it was considered a ‘dry’ season with rainfall falling to 37-56% of the long term mean, and the period encompasses most of the pasture growth and irrigation season.

1. Using the observed 2014/15 irrigation schedule for each commercial farming operation, how much pasture was produced and what were the estimated evaporation, transpiration and drainage losses?

2. How much water would have been required to prevent pasture production losses due to limited irrigation and then what would the evaporation, transpiration and drainage losses have been?

3. How could irrigation have been managed differently to maximise transpiration, and therefore pasture production, but minimise soil evaporation and drainage losses?

4. What is the relationship between the time of grazing and time of irrigation with regards to estimated evaporation and drainage losses, and how can understanding this be used to improve the effectiveness of irrigation water applied to the pasture?
6.2 Methods and Materials

Site descriptions for Larundel Dairy Farm, Three Springs Dairies and Pendo Farms were presented in Sections 3.2.1 to 3.2.3. The following sections provide a description of the 2014/15 climate conditions at the three sites and the modelling required to address questions 1-4, and therefore Objective 8.

6.2.1 2014/15 Climate

The 2014/15 season chosen was considered a dry year, therefore the extent of the dry climatic conditions has been quantified.

Rainfall at each of the three sites over the scenario period (01/07/2014-31/3/2015) was 44-63% less and \( \text{PET}_\text{e} \) was 11-23% greater compared with the LTM values (Table 6.1). Even with the applied irrigation at TSD, the combined rainfall and irrigation inputs over the scenario period were 23% less than the LTM rainfall, but at LDF and PF they were 13 and 24% higher, respectively.

<table>
<thead>
<tr>
<th>Field site</th>
<th>Rainfall (mm)(^{1,3})</th>
<th>Irrigation (mm)</th>
<th>PET(_e) (mm)(^{2,3})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>01Jul14-31Mar15 LTM</td>
<td>01Jul14-31Mar15</td>
<td>01Jul14-31Mar15 LTM</td>
</tr>
<tr>
<td>LDF</td>
<td>332 592</td>
<td>334</td>
<td>840 736</td>
</tr>
<tr>
<td>TSD</td>
<td>309 844</td>
<td>337</td>
<td>825 673</td>
</tr>
<tr>
<td>PF</td>
<td>290 550</td>
<td>393</td>
<td>830 749</td>
</tr>
</tbody>
</table>

Note 1: LTM rainfall data were sourced from NIWA’s virtual climate network (VCN) stations 20153 (LDF), 16989 (TSD), and 19019 (PF), for the period 1972-2013.

Note 2: LTM \( \text{PET}_\text{e} \) was calculated using Equation 2.42 with solar radiation, air temperature, relative humidity and wind speed data from NIWA’s VCN stations 20153 (LDF), 16989 (TSD), and 19019 (PF), for the period 1997-2013.

Note 3: Experimental period data were sourced from NIWA’s on-site meteorological stations 39224 (LDF), 37920 (TSD), and 38866 (PF). \( \text{PET}_\text{e} \) was calculated using Equation 2.42.

On average, irrigation was applied at rates of 5-9 mm at LDF, TSD and PF, respectively, every 3-4 days, as shown in Figure 6.1. From approximately mid-December 2014 to mid-March 2015, approximately 150 mm of rain fell at LDF compared with 84 mm at PF and 41 mm at TSD. This difference is reflected in the irrigation applied at LDF, which was 140 mm compared with 246 and 225 mm at TSD and PF, respectively.
Figure 6.1 Stacked daily precipitation including rainfall (■) and irrigation (■) for the period 01/07/2014-31/03/2015 at Larundel Dairy Farm (LDF), Three Springs Dairies (TSD) and Pendo Farms (PF).

NIWA quantify the potential evapotranspiration deficit (PED), accumulated from July to June, as a measure of drought (Mullan et al., 2005). The accumulated PED is the accumulated difference between PET and rainfall over 12 months from July to June, and therefore the amount of water that would need to be added to a crop over that period to prevent herbage production losses due to water shortage. In the calculations, an available water capacity of 150 mm is generally assumed. A 1-in-20 year PED is typically taken to be representative of a severe drought. In Canterbury the 1 in 20 year PED ranges from approximately 50 mm at the main divide to 600-800 mm along the eastern coastline (Figure 6.2).

For each of the three commercial dairy farms, the 1-in-20 year PED has been estimated from Figure 6.2 to be ~600 mm for LDF and PF and ~500 mm for TSD. Salinger (2003) also used PED to quantify the point at which the potential plant growth is unable to be sustained (i.e. 100 mm), and the point at which a significant loss of pasture production is likely (i.e. 150 mm). The method for calculating the PED is detailed in Appendix 30.
Figure 6.2 Potential evapotranspiration deficit (PED) (mm) with a 1 in 20 year return period across New Zealand, equivalent to a 5% chance of occurrence in any one year (Mullan et al., 2005).

Over the scenario testing period, the PED was calculated to be 683 mm at TSD, 730 mm at PF and 770 mm at LDF (Figure 6.3), which was greater than the annual 1-in-20 year PED for each of the sites. This highlights the ability of irrigation to prevent pasture production losses over the scenario period.

Table 6.1 shows 334-393 mm of irrigation was applied over the scenario period, less than the calculated PED values. This suggests that the level of irrigation at each of the three sites was insufficient to prevent water stress. However, as identified in Chapter 4, estimation of PET, from climate data only is likely to
over-estimate the actual crop demand (Section 4.3.5). Therefore, the amount of irrigation actually required to maintain potential pasture growth is likely to be less than the PED calculated.

6.2.2 Modelling

Over the scenario period, DairyMod was used to simulate pasture growth (Section 2.3.2.6). The SWW model was used to predict PET, (Section 2.4.2.4), with the DairyMod-simulated pasture LAI and height data. Soil water flow for each of the three dairy farms was simulated with HYDRUS (Section 2.3.3.4).

6.2.2.1 DairyMod

Single paddock simulations were run over the period 2003-2015. Simulations were run with 10 ‘loops’ to reduce the influence of the initial conditions (Johnson, 2013b). For the three commercial dairy farms the calibrated model from Chapter 3 was used (Table 3.9). Grazing schedules from the 2011/12 experiment were maintained for each site (Section 3.2.4.2), as were residual grazing heights (i.e. 1.5 t DM/ha for the first seasonal grazing, then 1.0 t DM/ha) and nitrogen fertiliser applications (Section 3.2.4.4), as there was nothing to suggest that this assumption was invalid. Soil hydraulic and physical properties determined for LDF (Table 3.7) and TSD and PF (Table 3.10) were maintained.

Pasture growth over the scenario period was simulated firstly using the measured irrigation data for each site (Figure 6.1), and then using the irrigation trigger function within the model (Section 2.3.2.6). This allowed the actual pasture production to be estimated, and then the potential production without water stress (Questions 1 and 2, Section 6.1). Within the irrigation module, the irrigation trigger function was set so that $g_{\text{water}}$ was maintained at a value of 1.0 over the scenario period. To achieve this, 10 mm of water was applied, with a minimum irrigation return interval of one day, once the plant available soil water fell below 80% relative to field capacity, to reflect the transpiration reduction function applied within the model.
To satisfy Question 3, DairyMod was used to predict irrigation demand under varying management conditions. DairyMod was used in preference to HYDRUS for this due to limitations within the HYDRUS-1D package for scheduling irrigation. This included the inability to set a minimum return interval and difficulties in triggering irrigation based on soil profile water content (Section 2.3.2.6).

A range of irrigation management conditions were tested, each of which included adjustments to the soil water content irrigation trigger level, the depth of irrigation water applied during each irrigation event and the minimum return interval. As illustrated in Table 6.2, for each trigger level tested, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55 and 60 mm of irrigation were applied during each irrigation event, with minimum return intervals of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11 and 12 days, respectively. Accordingly, the irrigation system capacity was set to a maximum of 5 mm/d. The management rules tested were based on the range applied by Bright (2009b). The simulated irrigation was then used in HYDRUS to simulate drainage and surface water runoff, soil evaporation and canopy transpiration under the different irrigation schedules, as detailed in Section 6.2.2.3.

<table>
<thead>
<tr>
<th>Trigger (%)</th>
<th>Irrigation depth applied (mm)</th>
<th>Minimum return interval (d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>5-60</td>
<td>1-12</td>
</tr>
<tr>
<td>60</td>
<td></td>
<td></td>
</tr>
<tr>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note 1: Trigger for irrigation based on a percentage of the available soil water.
Note 2: irrigation depths applied were increased in 5 mm intervals between 5-60 mm.
Note 3: minimum return intervals based on applying up to 5 mm/day of irrigation, as per Bright (2009b).

6.2.2.2 Shuttleworth-Wallace

The potential daily soil evaporation and canopy transpiration were estimated for each site with the Shuttleworth-Wallace model. The canopy data (LAI and pasture height) simulated by DairyMod for both the actual known irrigation schedule and the simulated irrigation schedule required to prevent water stress were used. Doing so provided an estimate of the actual PETc and maximum potential PETc for the pasture where water was not limiting as required for Questions 1 and 2. Where soil moisture was limiting due to insufficient irrigation under the ‘actual’ irrigation scenario, HYDRUS was used to adjust the SWW PETc estimations accordingly (SWWadj) (Section 2.3.3.4), as was done in Chapter 5.

For Questions 3 and 4, the maximum potential SWW PETc estimates from Question 2 were used as inputs to the HYDRUS model.

Climate data for the three sites over the scenario period were obtained from the on-site NIWA climate stations (Table 3.4).
HYDRUS was used in preference to DairyMod for simulating soil water flow through the soil profiles at each of the three sites. This was in response to the findings in Chapters 4 and 5, whereby HYDRUS was found to predict soil water flow more accurately due to its dedicated focus on soil water flow.

The HYDRUS simulations assumed one-dimensional, uniform water flow through the 700 mm soil profiles at the three sites. Each simulation was run for a period of 274 days over the scenario period. The calibrated model (Section 4.2.4.1) was used for the three sites. Soil hydraulic property values for LDF (Table 4.1), TSD (Table 4.4) and PF based on the Templeton (2) soil (Table 4.5), were maintained. The atmospheric boundary condition at each site involved actual daily precipitation, which included irrigation (Figure 3.2), and potential evaporation and transpiration rates calculated using the SWW model (Section 6.2.2.2). Standard field conditions were assumed, therefore water redistribution at the surface was permitted and free drainage from the base of the soil profiles was applied.

Profile drainage, surface water runoff and reductions in the SWW estimates of soil evaporation or canopy transpiration due to insufficient water availability over the scenario period were simulated firstly using the actual irrigation data for each site (Figure 6.1) to address Question 1 (Section 6.1). Each of the water balance components were then simulated in HYDRUS using the DairyMod predicted non-limiting irrigation schedule (Question 2). Once drainage, runoff, evaporation and transpiration had been quantified for Questions 1 and 2; HYDRUS was used to simulate drainage, runoff, evaporation and transpiration using the range of irrigation schedules determined with DairyMod to address Question 3.

For Question 4, the irrigation schedule was manually set whereby 20 mm of irrigation were applied to the pastures immediately following grazing or 1, 2, 3, 4, 5, 6, 7, 9, 11, 13, 15, 17, 19 or 21 days post grazing. For the TSD and PF sites, regrowth periods were 21 and 16 days, respectively. Therefore, the effects of applying irrigation on water losses and water use up to 19 and 15 days post irrigation were simulated for these sites, respectively. By assuming a single irrigation event for each regrowth cycle there was the potential for water limiting conditions to arise. However, a single irrigation event was necessary to be able to determine the influence of irrigation timing relative to grazing. The value of 20 mm for each irrigation event was selected to minimise the potential for water stress and limit the potential for over-irrigation, and therefore the potential for surface runoff and excessive drainage losses. Initially, irrigation depths of 10 mm then 15 mm were applied. These, however, were insufficient to maintain non-limiting conditions, and minimised soil evaporation and drainage and therefore prevented any trends from being identified.

6.2.3 Statistical Analysis

Statistical analysis of the data was conducted in GenStat (version 17, VSN International Ltd, 2013).
ANOVA procedures were used to compare changes in the total irrigation water applied, drainage and runoff losses, total canopy transpiration and soil evaporation with irrigation application depths and trigger levels. Where treatment means were significant ($\alpha=0.05$), they were separated using Fisher’s protected least significant difference (LSD) test. Unless otherwise specified, standard errors of the mean (SEM) were used to describe variation in the data within treatments.
6.3 Results

6.3.1 Estimated pasture production and evaporation, transpiration and drainage losses with the 2014/15 actual and simulated full irrigation

Simulated pasture production, with the actual irrigation, ranged from 5.5 t DM/ha at LDF to 12.5 t DM/ha at PF for the nine month period from 01/07/2014 to 31/03/2015 (Table 6.3). When annualised, through the addition of the simulated herbage yields for months April-June for the three sites from the 2011/12 data (Figure 3.22 for LDF and Figure 3.25 for TSD and PF), herbage production was estimated to be 7.2, 13.4 and 14.4 t DM/ha/y at LDF, TSD and PF, respectively. Reasons for the low simulated yields are discussed in Section 6.4.1.

At each of the three sites, despite irrigation being applied, $g_{\text{water}}$ fell below a value of 1 to a minimum of 0.87 for 25-46 days over the scenario period. Accordingly, pasture growth was potentially limited due to water stress (Figure 2.5). However, when irrigation was triggered to prevent $g_{\text{water}}<1$, the simulated herbage yields increased by only 0.04-0.12 t DM/ha (Table 6.3), indicating that while water stress may have occurred, its effect was minimal.

When the accumulated actual and DairyMod-simulated irrigation for the three dairy farms were compared (Table 6.3) it appears that 37-154 mm less irrigation was required than what was actually applied to maximise herbage production. The reduced irrigation also led to a lower total drainage over the scenario period, with reductions of 10-76% (14-101 mm) (Table 6.3). However, the total soil evaporation and canopy transpiration differed by only 1-7 mm. Runoff losses with both the actual and simulated irrigation was negligible over the scenario period at <1 mm for each of the three sites, and therefore have not been presented.

These results suggest that less water could have been applied if irrigation had been managed more effectively, without any production losses, and in consequence, the amount of drainage could have been reduced. This is discussed further in Section 6.4.1.

Without irrigation, the simulated herbage yields were reduced to 3.6-5.7 t DM/ha, drainage to 25-92 mm and canopy transpiration and soil evaporation to 210-285 mm and 83-119 mm over the nine month scenario period, respectively (Appendix 31).
Table 6.3  Total actual irrigation (I<sub>act</sub>), DairyMod-simulated (I<sub>sim</sub>) non-limiting irrigation, DairyMod-simulated herbage yields, HYDRUS-simulated soil profile drainage and SWW estimated soil evaporation and canopy transpiration with I<sub>act</sub> and I<sub>sim</sub> for the period 01/07/2014-31/03/2015 at Larundel Dairy Farm (LDF) Three Springs Dairies (TSD) and Pendo Farms (PF).

<table>
<thead>
<tr>
<th>Site</th>
<th>Irrigation (mm)</th>
<th>Herbage yield (t DM/ha)</th>
<th>Drainage (mm)</th>
<th>Soil evaporation (mm)</th>
<th>Canopy transpiration (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>I&lt;sub&gt;act&lt;/sub&gt;</td>
<td>I&lt;sub&gt;sim&lt;/sub&gt;</td>
<td>I&lt;sub&gt;act&lt;/sub&gt;</td>
<td>I&lt;sub&gt;sim&lt;/sub&gt;</td>
<td>I&lt;sub&gt;act&lt;/sub&gt;</td>
</tr>
<tr>
<td>LDF</td>
<td>334</td>
<td>180</td>
<td>5.4</td>
<td>5.5</td>
<td>134</td>
</tr>
<tr>
<td>TSD</td>
<td>337</td>
<td>300</td>
<td>12.0</td>
<td>12.0</td>
<td>145</td>
</tr>
<tr>
<td>PF</td>
<td>393</td>
<td>250</td>
<td>12.5</td>
<td>12.6</td>
<td>134</td>
</tr>
</tbody>
</table>

6.3.2 Irrigation management to maximise herbage yield and transpiration and minimise soil evaporation and drainage losses

Detailed total irrigation, drainage, runoff, canopy transpiration, soil evaporation and herbage yield values for each irrigation scheduling scenario at the three sites are given in Appendix 31.

6.3.2.1 Irrigation

At each site, the total irrigation applied increased (P<0.001) with increases in the depth of each irrigation application and associated return interval, and as the irrigation trigger level increased (Figure 6.4). However, at the lower application depths (i.e. ≤20 mm) and trigger levels (i.e. 50-60%), there were no differences in the total irrigation applied. For example, the total irrigation increased from 177±42.8 mm to 483±42.8 mm at LDF, 243±50.5 to 596±50.5 mm at TSD and 248±39.5 mm to 590±39.5 mm at PF when 5-20 mm of water was applied with minimum return intervals of 1-4 days compared with when 50-60 mm was applied with minimum return intervals of 10-12 days, respectively. When the trigger level increased from 50-60% of the available soil water to 90% of the available soil water, the total irrigation increased from 157±27.6 to 558±27.6 mm at LDF and 207±32.6 to 810±32.6 mm at TSD and from 224±25.5 at a trigger level of 50% at PF to 635±25.5 mm at a trigger level of 90%. At the higher application depths and trigger levels (Figure 6.4), the simulated irrigation applied was unrealistic in a practical sense, reaching maximums of >1000 mm when irrigation was applied at a trigger level of 90% and depths of 60 mm.
6.3.2.2 **Drainage and runoff**

The simulated drainage (Figure 6.5a) increased ($P<0.001$) with the irrigation application depth and return interval, which coincided with an increase in the total irrigation applied (Figure 6.4). Where irrigation was applied at depths of ≤20 mm per irrigation event, the total drainage was 40±41.4 mm at LDF, 136±34.4 mm at TSD and 58±42.8 mm at PF. The results also indicate that when trigger levels of 50-60% were applied the drainage losses were 35-107 mm across the three sites compared with up to 610 mm at higher trigger levels. Accordingly, where irrigation was applied at depths of no more than 20 mm and at irrigation trigger levels of ~60%, the estimated drainage from irrigation and rainfall was comparable to that estimated under rain fed only conditions (Appendix 31).

For a number of the irrigation schedules tested, the irrigation application depths exceeded the soil moisture deficit at the selected trigger level. For example, when the soil moisture content fell to 50% of the total available water capacity, the soil moisture deficit at the three sites was 39 mm (LDF), 53 mm (TSD) and 62 mm (PF) (Table 6.4). Accordingly, when the amount of irrigation water applied exceeded these deficits, excess irrigation water was lost from the profile as drainage, and therefore these scenarios need not be considered.

<table>
<thead>
<tr>
<th>Trigger (%)</th>
<th>LDF soil moisture deficit (mm)</th>
<th>TSD soil moisture deficit (mm)</th>
<th>PF soil moisture deficit (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>39</td>
<td>53</td>
<td>62</td>
</tr>
<tr>
<td>60</td>
<td>32</td>
<td>43</td>
<td>50</td>
</tr>
<tr>
<td>70</td>
<td>24</td>
<td>34</td>
<td>37</td>
</tr>
<tr>
<td>80</td>
<td>15</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>90</td>
<td>8</td>
<td>16</td>
<td>13</td>
</tr>
</tbody>
</table>
Runoff over the simulation period was negligible at all three sites at <1.0 mm (Figure 6.5b), and therefore has been excluded from the remainder of the results and discussion.

### 6.3.2.3 Canopy transpiration and soil evaporation

Irrespective of the total amount of irrigation applied or the irrigation schedule, the effect on the simulated canopy transpiration (Figure 6.5c) and soil evaporation (Figure 6.5d) at PF was minor at <1 mm. At LDF and TSD, transpiration and evaporation both increased with the irrigation applied, until the irrigation applied was sufficient to maintain them at their potential rates.

Transpiration was maximised when irrigation was applied at depths of 40-60 mm at LDF and 35-60 mm at TSD or with minimum trigger levels of 80-90% at LDF and 70-90% at TSD. However, the differences (P<0.001) in transpiration over the simulation period with irrigation depths of 5-25 mm at LDF (395±2.8 mm) and TSD (364±4.9 mm) compared with 413±2.8 mm at LDF and 382±4.8 mm at TSD were in actuality small (i.e. 20 mm). Similarly, when the irrigation trigger level was 60% at LDF, transpiration was 398±1.8 mm compared with 414±1.8 mm with a trigger of 80-90%, a difference of only 16 mm. At TSD, there was a difference of 16 mm in the simulated transpiration over the simulation period when a trigger level of 60% was applied (368±3.1 mm) compared with a trigger level 70-90% (384±2.1 mm).

At both sites, transpiration was lowest (P<0.001) when an irrigation depth of 5 mm and trigger level of 50% were applied. Overall however, the results indicate that for the scenarios tested, the effects on the canopy transpiration are relatively small.

Soil water evaporation losses were minimised when irrigation was applied at depths of 20 mm or less at LDF (140±1.0 mm) and 25 mm or less at TSD (114±2.9 mm), and when the trigger level was set to 50% of the available soil water. Differences between the lowest and highest evaporation amounts over the scenario period were no more than ~14 mm and ~48 mm at LDF and TSD, respectively.
6.3.2.4 Herbage yield

At all three sites, the total simulated herbage yield varied with irrigation managements (Figure 6.5e).

The DairyMod-simulated herbage yield was maximal when 10-20 mm was applied with a minimum return interval of 2 days across all three sites, or at trigger levels of 60-70% at LDF and 80-90% at TSD and PF. At LDF a maximum yield of 5.5 t DM/ha was achieved compared with 12.2 t DM/ha at TSD and 12.7 t DM/ha at PF, equal to those modelled under non-stressed conditions for Question 2 (Table 6.3). However, while differences in yield occurred at each site with the irrigation application depth (P<0.001) and trigger level (P<0.001), they were small. For example, at LDF the total yield achieved when 10-20 mm of irrigation were applied during each irrigation event averaged 5.5±0.03 t DM/ha compared with 5.3±0.03 t DM/ha when the irrigation scheduling involved irrigation application depths of 55-60 mm per event. At TSD, however, differences in yield were only 0.3±0.10 t DM/ha when 5-25 mm of irrigation were applied compared with 30-60 mm, but were 1.9±0.06 t DM/ha when the trigger level was 50% compared with 80-90%.
6.3.3 Influence of the timing of irrigation with regard to grazing on soil evaporation and drainage

The timing of irrigation with regard to grazing was found to influence the total drainage from the soil profile, but there was a limited effect on soil evaporation and canopy transpiration (Figure 6.6). At each of the three sites, there was a decline in the total drainage as the delay in irrigation increased from when the pasture was grazed. At LDF, there was a 31% (16 mm) decrease in the total drainage when irrigation was applied 21 days following grazing ($I_{21}$) compared with immediately after grazing ($I_0$). For TSD and PF there was a 12% (16 mm) and 24% (19 mm) decrease in the total drainage when irrigation was applied 19 ($I_{19}$) and 15 ($I_{15}$) days post grazing, respectively, compared with on the day the pasture was grazed.

The total soil water evaporation for $I_{21}$ and $I_{15}$ at LDF and PF, respectively, remained within 1 mm of that for $I_0$. At TSD, there was a small 7% (7 mm) decline in the total evaporation when irrigation was delayed by 19 days. Canopy transpiration changed by no more than 2% (0-6 mm) at each of the three sites, irrespective of the timing of irrigation relative to grazing.

![Figure 6.6](image)

**Figure 6.6** HYDRUS-simulated drainage (a), soil evaporation (b) and canopy transpiration (c) against the number of days post grazing that irrigation was applied at Larundel Dairy Farm (▲), Three Springs Dairies (●) and Pendo Farms (◆). 20 mm of irrigation was applied during each irrigation event. Only one irrigation event per regrowth period was scheduled.

Changes in the daily accumulated simulated drainage over the scenario testing period when irrigation was applied immediately following grazing ($I_0$) and 7 days ($I_7$) post grazing and 21 (LDF), 19 (TSD) and 15 (PF) days post grazing at the three sites is illustrated in Figure 6.7.

As the timing between grazing and irrigation increased, drainage was delayed and the amount of drainage in response to each irrigation event reduced. For example, at TSD $I_0$ irrigation on the 19/10/2014 led to up to ~10 mm of drainage, compared with 3 and <1 mm when irrigation was applied 7 and 19 days post grazing. At PF, $I_0$ irrigation on the 08/10/2014 led to up to ~15 mm of drainage, compared with 11 and 3 mm when irrigation was applied 7 and 15 days post grazing. Drainage from
the profile ceased for each of the simulations mid-November 2014 at LDF, mid-December 2014 at TSD and mid-February 2015 at PF due to sufficient soil moisture deficits within the soil to retain any inputs of water.

![Figure 6.7](image)

**Figure 6.7** Accumulated HYDRUS-simulated drainage at Larundel Dairy Farm (LDF) (a), Three Springs Dairies (TSD) (b) and Pendo Farms (PF) (c) for the period 1/07/2014 to 31/3/2015. Irrigation was applied immediately following grazing (---), 7 days post grazing (—) and 21 (LDF), 19 (TSD) and 15 (PF) days post grazing (----). Each grazing date is indicated (✦). 20 mm of irrigation was applied during each irrigation event. Only one irrigation event per regrowth period was scheduled.

### 6.3.4 Irrigation scheduling validation

To validate the results of the scenario testing, the irrigation schedule that applied 15 mm of water with a minimum return interval of three days, once the available soil moisture content reached 60%, relative to field capacity, was selected for each of the three sites, based on the scenario testing results. The schedule was then manually adjusted to delay irrigation post grazing, prevent irrigation within 14 days following grazing at LDF and TSD and within 10 days at PF, due to the shorter rotation periods. This delay of 10-14 days equated to irrigating once the pasture had reached ~1.7 t DM/ha, following grazing to 1 t DM/ha. Table 6.5 compares the actual irrigation applied and simulated herbage yield, drainage, soil evaporation and canopy transpiration using the actual irrigation schedule over the 2011/12 lysimeter experimental period, with that simulated using the optimised irrigation schedule.

The results presented in Table 6.5 indicate that the total irrigation applied could have been reduced by 90 mm at LDF and 113 mm at TSD, without adversely impacting on herbage production. At PF, the simulated irrigation was higher than that actually applied, confirmation that the pasture was subject to water stress during the lysimeter experiment (Section 4.4.1). However, the additional irrigation led to the simulation of only 1 t DM/ha/y more production. At LDF and TSD herbage yields differed by a minor 0.1-0.6 t DM/ha. As was observed in the scenario testing (in Figures 6.5 and 6.6), optimising irrigation had a minor effect on the total soil evaporation and transpiration over the experimental period. In contrast, the total drainage was reduced by 14% (50 mm) at LDF and 18% (113 mm) at TSD.
Table 6.5 Total actual irrigation ($I_{\text{act}}$) and optimised ($I_{\text{opt}}$) non-limiting irrigation, DairyMod-simulated herbage yields, HYDRUS-simulated soil profile drainage and SWW estimated soil evaporation and canopy transpiration with $I_{\text{act}}$ and $I_{\text{opt}}$ for the period 09/09/2011-14/09/2012 at Larundel Dairy Farm (LDF) Three Springs Dairies (TSD) and Pendo Farms (PF).

<table>
<thead>
<tr>
<th>Site</th>
<th>Irrigation (mm)</th>
<th>Herbage yield (t DM/ha)</th>
<th>Drainage (mm)</th>
<th>Soil evaporation (mm)</th>
<th>Canopy transpiration (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_{\text{act}}$</td>
<td>$I_{\text{opt}}$</td>
<td>$I_{\text{act}}$</td>
<td>$I_{\text{opt}}$</td>
<td>$I_{\text{act}}$</td>
</tr>
<tr>
<td>LDF</td>
<td>225</td>
<td>135</td>
<td>10.3</td>
<td>10.2</td>
<td>349</td>
</tr>
<tr>
<td>TSD</td>
<td>173</td>
<td>60</td>
<td>12.00</td>
<td>12.6</td>
<td>617</td>
</tr>
<tr>
<td>PF</td>
<td>144</td>
<td>225</td>
<td>14.9</td>
<td>15.9</td>
<td>131</td>
</tr>
</tbody>
</table>
6.4 Discussion

The aim of this chapter was to investigate how the irrigation of pasture can be managed to improve irrigation efficiency and on-farm productivity. This was done by firstly quantifying the amount of irrigation water applied and estimating the amount of irrigation required to prevent canopy stress. Their influence on drainage, soil evaporation and canopy transpiration losses and on herbage yields was then assessed across three commercial dairy farms in Canterbury. A range of irrigation scheduling scenarios were tested to quantify the effects of irrigation depths, return intervals, trigger levels and irrigation timing with respect to the timing of grazing on drainage, soil evaporation and canopy transpiration losses and on herbage yields on each of the three dairy farms. From the results, an optimised irrigation schedule was identified.

6.4.1 Simulated 2014/15 pasture production and water use

Despite maintenance of the same grazing and fertiliser managements as the 2011/12 lysimeter experiment, and non-limiting water conditions, the 2014/15 simulated, annualised herbage yields (Section 6.3.1) were 48%, 5% and 12% lower at LDF, TSD and PF, respectively, than those simulated in the 2011/12 experiment (Table 6.5). An analysis of monthly averaged growth rates indicated growth during the 2011/12 experiment was up to 82% greater. These differences in growth rate coincided with 2-19% higher average monthly temperatures, especially from January-March during the 2014/15 scenario period. When daily maximum temperatures during the 2014/15 scenario period were compared with the DairyMod high temperature stress functions (Sections 2.3.2.6 and 3.2.6), the initial high temperature stress values were exceeded 31 days over the scenario period at LDF and 33 and 39 days at TSD and PF, respectively. Accordingly, it was concluded that temperature, the effects of which are detailed in Section 2.3.2.3, was at times limiting to pasture growth in 2014/15.

With the actual irrigation schedule, pasture production and canopy transpiration results were comparable to when irrigation was simulated to prevent water stress (Table 6.3). This highlighted that the irrigation water supplied to the pasture at the three sites over the 2014/15 irrigation season was largely sufficient to minimise production losses, despite drought conditions (Section 6.2.1). However, the simulations identified that the actual irrigation could have been reduced by 37-154 mm (11-46%), while still maintaining the same (or slightly greater) level of production. Accordingly, the lower total irrigation required led to a reduced total drainage at all three sites, which carries with it implications for improved groundwater quality through the potential to reduce nitrate leaching (Chapter 7).

6.4.2 Optimised irrigation scheduling

The results indicate that management of irrigation to minimise non-productive losses of water (i.e. drainage below the root zone, surface runoff and soil water evaporation) should focus on reducing
drainage, as this varied to the greatest degree with management. In contrast, adjustment of irrigation practices to reduce soil water evaporation had a relatively small influence, especially at LDF and PF. At TSD, evaporation varied to the greatest degree among irrigation scenarios. This was a response to insufficient irrigation when irrigation was applied at a trigger level of 50% or with return intervals of 10-12 days, which lead to a drier soil profile and reduced yields (Figure 6.5).

To reduce drainage losses it appears that applications of up to 20 mm were most effective. For the irrigation supply to be sufficient to maximise transpiration and herbage production, at least 10 mm of irrigation applied with a minimum return interval of 2 days and trigger level of ~60% was required. A trigger level of 60% also helped reduced drainage losses, with minimal effect on the total canopy transpiration. At TSD, however, a trigger level of 60% did lead to a small reduction in the potential herbage yield (~0.6 t DM/ha) when compared with a trigger level of 80-90%, but to a lower total drainage of 121 mm of drainage compared with 315-610 mm. An irrigation schedule where 10-20 mm of water is applied with a minimum return interval of 2-4 days, at a trigger level of 60% and irrigation delayed post grazing, is therefore advocated. Validation of this optimised schedule across the three sites over the 2011/12 experiment period supported the findings of the 2014/15 scenario testing. Overall, drainage reductions of 37-82% (average of 61%) were achieved in 2014/15 across the three sites and 14-18% at LDF and TSD in 2011/12 due to the need for less irrigation water when is applied strategically.

6.4.2.1 Irrigation requirements

Based on the optimised irrigation schedule, the total irrigation applied over the 2014/15 irrigation season (until 31 March 2015) could have been reduced to 120 mm at LDF, 165 mm at TSD and 210 mm at PF. Accordingly, 214 mm (64%), 53 mm (36%) and 183 (47%) less irrigation at LDF, TSD and PF, respectively, could have been applied than what actually was, while maintaining a similar level of herbage production (Table 6.3, Appendix 31). However, even without water stress, the simulated herbage yields were approximately 25-50% of potential yields reported for Canterbury (Section 2.3.2.1). The same nitrogen fertiliser management schedules from the 2011/12 lysimeter experiment were adopted, which led to nitrogen-limited pasture growth at all three sites (Sections 3.4.1.7 and 3.4.3). It therefore follows that nitrogen deficiency, in addition to temperature stress, was again likely to be a contributing factor to the low 2014/15 herbage yields. Due to the limitations within DairyMod in simulating a response to nitrogen with the calibrated model temperature parameter values, the nitrogen required to maximise yields was not able to be estimated. However, based on the Lincoln University Dairy Farm nitrogen use (LUDF, 2015), and the results of the irrigated, fertilised treatment in Chapter 5, it is predicted that ~350-400 kg N/year would have been required.

As the managements of the three dairy farms included in the current experiment were representative of the range of dairy farm managements that exist across Canterbury, it is likely that this finding is
applicable to many commercial dairy farms region wide, and has therefore been discussed further in Chapter 7.

6.4.2.2 Influence of irrigation schedules on soil evaporation losses

The relatively small changes in soil evaporation with changes in the irrigation schedule were in part due to the high proportion of the simulated evaporation being due to rainfall, and the regularity of the rainfall. At LDF, for example, of the 147 mm under the actual irrigation scenario and the 134 mm under the optimised irrigation schedule, 119 mm (~85%) would have occurred without irrigation, leaving 15-28 mm of soil evaporation being in response to irrigation. At TSD and PF, the basal (or rain-based) soil evaporation was 83 and 106 mm, equating to 60-81% of the simulated evaporation with the actual (139 and 144 mm) and optimised (102 and 144 mm) irrigation schedules, respectively. These results support the findings of Sim (2014) who field tested to see if different defoliation regimes (i.e. set-stocked and rotational grazing) over spring would influence the water use of lucerne. The results suggested that the total water use (soil evaporation and canopy transpiration) was relatively unaffected due to the influence of regular rainfall events maintaining the soil water content of the upper soil layer, and therefore minimising the potential for evaporation reductions.

For the irrigation-based component of the soil evaporation, no matter which irrigation schedule was applied, the evaporation did not vary at PF. This suggests that the irrigation scheduling at this site was sufficient to maintain adequate moisture levels at the soil surface to allow for evaporation at the potential rate throughout the scenario period. At TSD and LDF, the variation of up to 13 and 48 mm, respectively, between irrigation schedules suggested that the greater the irrigation application depth, the greater the soil evaporation. This contrasted with what was expected, in that it was anticipated that larger depths of irrigation water applied less frequently would allow the soil surface to dry between irrigations, and therefore limit the potential for evaporation. On the other hand, smaller but more frequent irrigations were expected to maintain a higher soil moisture at the surface and therefore lead to more soil evaporation. Mermoud et al. (2005), for example, reported 9-28% increases in soil evaporation when irrigation schedules were compared. However, in the current experiment, the smaller more frequent irrigations led to a greater number of days where the surface soil moisture was below the critical level for evaporation to occur (Section 2.3.3.4) and often was not sufficient to restore the water content in the immediate vicinity of the soil surface above the critical level, particularly at the lowest trigger level of 50%. Conversely, with increasing irrigation depths, the applied irrigation maintained the soil water content at or near the surface above the critical level (Section 2.3.3.4) for longer periods, reducing the total number of days the surface soil moisture was below the critical level. For example, at TSD, at a trigger level of 50% the number of irrigation events reduced from 32 when irrigation was applied at depths of 5 mm to seven when irrigation was applied at depths of 25 mm or more. At 5 mm depths, the total soil evaporation was 102 mm compared with 112 mm and 132 mm
when irrigation was applied at depths of 35 mm and 60 mm, respectively. The increase in evaporation was reflected by a decrease in days where the surface soil moisture was at or below the critical level, being 50 days (5 mm), 47 days (35 mm) and 11 days (60 mm). On the 11/01/2015, for example, two days following the application of 5 mm of irrigation, the surface soil moisture had fallen to the critical level. However, when 30 mm of irrigation was applied on the same date, the critical level at the soil surface was not reached until six days following the irrigation. When 55 mm was applied, the critical level was not reached for 13 days.

The difference in the results between the current experiment and that reported by Mermoud et al. (2005) arose due to differences in the experimental design and climatic differences. Mermoud et al. (2005), for example, applied small (8 mm) amounts of irrigation every day and compared that with applications twice a week of a greater (unspecified) depth, determined from pan evaporation data. The experiment was based in the semi-arid region of West Africa. In the current experiment, while daily applications of 5 mm were possible, irrigation was triggered based on the soil moisture content, which meant irrigation on successive days was largely avoided, and enabled the surface to dry out. Accordingly, where daily irrigation is compared with less frequent irrigation, it is likely, as reported by Mermoud et al. (2005), that surface evaporation would decline with the reduction in irrigation frequency. However, when irrigation is based on maintaining a set soil moisture content to prevent canopy stress, as simulated by the current experiment, inputs of water to the surface are less frequent, and therefore will not necessarily follow the same trend. This was tested at TSD. Irrigation was applied in depths of 5 mm daily, 10 mm every two days, 15 mm every three days, with subsequent 5 mm increases up to 60 mm every 12 days. However, for all three scenarios, the total evaporation remained at the maximum of 139 mm. The semi-arid environment of the research by Mermoud et al. (2005), which resulted in an average evapotranspiration rate of 6 mm/d compared with an average of ~2 mm/d at the three lysimeter sites over the 2014/15 scenario period, likely enabled the soil surface to dry out to a greater extent between irrigations, and therefore led to the soil evaporation reductions.

6.4.2.3  Influence of irrigation schedules on drainage losses

Optimisation of the irrigation scheduling highlighted the potential to reduce drainage through reduced irrigation requirements and by irrigating only once a set soil moisture trigger level (i.e. 60%) has been reached. At all three sites, the simulated drainage under the optimised irrigation schedule was approximately equal with that under rain fed only conditions (Appendix 31), and therefore unable to be reduced further irrespective of how or when irrigation is applied. Again, these reductions in drainage have implications for groundwater quality, in that a reduction in water flow below the root zone has the potential to reduce the transport of pollutants, for example nitrates, into groundwater (Chapter 7).
Differences in drainage between the different irrigation schedules tested arose in response to the
differences in application depths and the total irrigation applied. As illustrated in Figure 6.5a, as the
total depth of irrigation applied, and therefore the individual irrigation event depths (Figure 6.4)
increased, so too did the drainage. According to Martin et al. (2006), over-application of irrigation
water leads to unnecessary drainage losses. This occurred on a number of occasions throughout the
scenario testing where the irrigation water applied exceeded the moisture deficit of the soil at the set
irrigation trigger level (Table 6.4). In other instances, a number of the irrigation schedules tested
prevented irrigation from being applied in excess of the available storage capacity of the soil. For
example, at a trigger level of 60% and application depths of 30 mm (LDF), 40 mm (TSD) and 50 mm
(PF), the irrigation applied returned the soil moisture to or near field capacity. In doing so, subsequent
rainfall inputs of water were unable to be stored by the soil and therefore triggered drainage below
the root zone. In contrast, with the optimised irrigation schedule, where 15 mm irrigation was
simulated to occur once the available soil moisture fell to 60%, deficit irrigation was allowed for. At
the 60% trigger level, 32-50 mm of available storage capacity existed across the three sites (Table 6.4),
leaving a deficit of at least 17 mm following irrigation. In doing so, subsequent inputs of water from
rainfall up to the soil moisture deficit could be stored by the soil.

6.4.3 Influence of irrigation timing relative to grazing on non-productive water losses

6.4.3.1 Drainage

The effect of irrigation timing with respect to grazing on drainage was that more water was lost via
drainage the sooner the pasture was irrigated following grazing (Figure 6.7). This occurred as a direct
response to the demand for water by the pasture, whereby the water requirement of a pasture
immediately post-grazing is reduced compared with one that has regained full ground cover. Therefore
there is less uptake of water from the soil, allowing greater drainage to occur. By understanding this,
the timing of irrigation can be managed to minimise drainage losses. From the scenario testing it
appears that drainage will continue to decline as the time interval between grazing and irrigation
increases. A period of 10-14 days (or once ~1.7 t DM/ha is reached) could minimise drainage losses,
however is not always practical without compromising herbage production. For example, in the
validation of the optimised irrigation schedule over the 2011/12 experiment at PF, up to three
irrigation events were triggered between grazings. Accordingly, the minimum delay in irrigation post
grazing that was able to be achieved was 5 days. Similarly at TSD and LDF, on some occasions irrigation
could only be delayed by 5-9 days without adversely affecting herbage production. Accordingly, when
the optimised irrigation schedule was applied, with or without manual adjustments to delay irrigation,
the amount of drainage was the same at TSD and PF. At LDF, delaying the irrigation reduced drainage
by 5 mm more than if the optimised schedule had been applied without delaying irrigation.
6.4.3.2 Soil surface evaporation

The timing of irrigation with regard to grazing had only a small influence on soil evaporation, with differences of no more than 8 mm between simulation runs over the scenario period. This again contrasted with what was expected. When irrigation was applied immediately post grazing, it was expected that evaporation of water from the soil would have been elevated due to a low ground cover compared with when irrigation was applied several days following grazing, once the pasture had re-established ground cover. The lack of change, however, can be in part attributed to the influence of rainfall throughout the scenario period. As discussed, rainfall at each of the three sites was sufficient that without irrigation 85% (LDF), 81% (TSD) and 74% (PF) of the optimised irrigation simulated evaporation would still have occurred (Appendix 31). Accordingly, the rainfall minimised the influence of the irrigation timing, although to a reduced degree at TSD. This was because, unlike LDF and PF, during the peak of the growing season (December-March), rainfall at TSD was lower and less frequent than at LDF and PF (Figure 6.1). Therefore, this enabled differences in the timing of grazing to be identified. At LDF and PF, the more consistent and higher rainfall over the same period effectively ‘masked’ the effects of irrigation timing on soil evaporation losses. In an average rainfall year, the influence of rainfall is likely to be higher, further reducing the effect of irrigation timing with regard to grazing on evaporation losses. Overall, however, for the 2014/15 drought affected scenario period, the influence of soil evaporation was small.

6.4.4 Feasibility of the proposed optimised irrigation scheduling

Within a modelling context, strategic irrigation, such as that proposed by the optimised irrigation schedule, is relatively straightforward to apply. However, on-farm, the practicality of doing so is less simple. This is largely attributable to the irrigation system design, water security and the lack of, or limited, on-site soil moisture monitoring.

Within the South Island of New Zealand, spray irrigation accounts for ~74% of the irrigated area (Powers, 2012), of which it is expected that centre pivot irrigation makes up a large proportion. As illustrated by the three farms included in the lysimeter experiment, 3.5-6.6 mm of water was applied every 2-5 days, although at times depths of up to 15 mm were applied (Section 3.2.3.1). This suggests that standard irrigation practice within Canterbury is for low (i.e. ~5mm) applications of water, applied every 3-4 days, which is also suggested as typical for centre pivot systems by INZ (2007).

The design of such systems limits their flexibility to irrigate according to canopy demand. In general, a pivot-based system will move around the farm, irrigating paddocks in a sequential order, on a set schedule. It follows, therefore, that the ability to delay irrigation based on when an individual paddock is grazed, or irrigate based on the water needs of an individual paddock, is limited, although with the introduction and uptake of variable rate irrigation (VRI) technology this may to a degree be overcome.
The use of the optimised irrigation schedule is further complicated for irrigation systems, such as LDF, that are reliant on irrigation scheme water, which become subject to restrictions. In such instances, delaying irrigation to develop a deficit within the soil profile and to prevent drainage losses can be viewed as impractical. Rather, creating a buffer to reduce the severity of restrictions becomes paramount.

To irrigate at a set soil moisture deficit, for example, when the available soil water falls to 60% as suggested by this thesis, also adds difficulty, particularly where soil type or physical properties vary within a property. To do so would require, at a minimum, soil moisture monitoring across each of the dominant soil types across the irrigated property or ideally, soil moisture monitoring of the dominant soil type within each paddock. This would enable improved paddock by paddock understanding of irrigation demand, and therefore more efficient management of irrigation water.

A limiting aspect to the proposed delay in irrigation is that the soil moisture may be reduced such that production is compromised. At PF, for example, it was found that a delay in irrigation of no more than five days was able to be achieved without compromising herbage production. However, a deficit approach should still be maintained to prevent unnecessary drainage losses.
6.5 Conclusions

The results from this chapter addressed Objective 8, in that they have quantified the influence of irrigation depths, return intervals, trigger levels and irrigation timing on drainage, runoff and soil evaporation losses and canopy transpiration and herbage accumulation across three commercial dairy farms in Canterbury. From these, a number of conclusions can be drawn.

The actual total irrigation applied at each of the three commercial dairy farms was sufficient to prevent significant production losses. However, it was identified that the amount of irrigation actually required was up to 76% less than that applied.

By reducing irrigation, drainage losses below the root zone were reduced. The effectiveness of the irrigation water applied was therefore improved and the potential for nitrate leaching to groundwater was minimised, which is discussed in Chapter 7.

It was identified that by applying irrigation at a depth of 10-20 mm, triggered when the available soil moisture fell below 60% relative to field capacity, irrigation efficiency was optimised through maximising herbage yields and reducing drainage and evaporation losses, for all three soil types. Delaying irrigation for 10-14 days post grazing also had the potential to minimise drainage losses. However, delaying irrigation by 10-14 was not always practical due to soil water content restrictions.

Contrary to what was expected, where sufficient water was applied to the soil to prevent canopy stress, irrigation scheduling had a minimal influence on soil evaporation losses, due to rainfall influences.

The timing and depth at which irrigation water was applied, so long as it was sufficient to meet canopy needs, did not influence the amount of herbage production achieved. However, temperature stress was found to be a limiting factor during the 2014/15 growing season, although nitrogen was the dominant limiting factor. Accordingly, the results indicate that while less irrigation water was required, nitrogen fertiliser needed to be increased to achieve optimum yields. This too is discussed in Chapter 7.
Chapter 7
General Discussion and Conclusions

7.1 Introduction

The review of previously published work (Chapter 2) identified an absence of recent research into the role of the leaf canopy in modelling evapotranspiration from a grazed, irrigated perennial ryegrass-based dairy pasture. The research in this PhD was then used to show that the common approach to modelling evapotranspiration, which assumes a constant crop leaf cover and largely ignores the potential for soil evaporation, led to poor and inconsistent predictions of water use. The null hypothesis of a common crop coefficient across the Canterbury Plains for accurately modelling evapotranspiration was rejected (Chapter 4) from the results of two experiments. A lysimeter-based experiment that incorporated three commercial dairy farms in Canterbury quantified pasture growth and water use and was used to test models of crop water use (Chapters 3 and 4). A second controlled experiment used a perennial ryegrass-based pasture with treatments of irrigation and nitrogen at Lincoln University to validate the farm results (Chapter 5).

This chapter pulls together the results and discussions of Chapters 3-6 and draws conclusions regarding the estimation of evapotranspiration for irrigated dairy pastures in Canterbury. The implications of the results of this research in terms of the allocation and management of irrigation water in Canterbury are also examined, and areas for further research are identified.

7.2 General discussion

7.2.1 Pasture growth – observed and simulated

The lysimeter-grown perennial ryegrass pasture from two of the lysimeters at LDF was similar to that grown in the wider paddock but, due to limiting nitrogen conditions, production was below the potential maximum of >20 t DM/ha for Canterbury (Black & Murdoch, 2013). Over the study period, 09/09/2011-07/09/2012, the total herbage yield was ~10.8 t DM/ha (Section 3.3.1). Analysis of the herbage yield accumulation using Tt showed the pasture produced 3.9 kg DM/ha/*Cd (Section 3.3.3), which was below the 7.2 kg DM/ha/*Cd determined for a non-limited cocksfoot pasture (Mills, 2007) and 7.5 kg DM/ha/*Cd for a perennial ryegrass pasture in Chapter 5 (Table 5.11), but similar to the 4-6.5 kg DM/ha/*Cd observed in Chapter 5 (Table 5.11) and reported by Tonmukayakul (2009) for nitrogen-limited ryegrass pastures. Based on a potential rate of ~7.0 kg DM/ha/*Cd it was estimated that the herbage production could have increased by 47% above that measured. However, this would
have required nitrogen fertiliser applications to have been doubled to ~420 kg N/ha/y to achieve an NNI of at least 0.8 (Section 3.4.1.3).

In the literature it has been reported that some C₃ species control leaf extension relative to nitrogen availability to optimise photosynthetic efficiency (Section 2.3.2.4), although this does not appear to have been tested for perennial ryegrass. At LDF, it was observed that the pasture, in general, maintained a nitrogen content of ~3%, and subsequently photosynthetic efficiency at ~80%, despite being nitrogen-deficient. These results suggest that this is the level of N that perennial ryegrass may try and maintain. Further research for perennial ryegrass is required to separate the pseudostem and leaf nitrogen contents, as carried out by Mills (2007) for cocksfoot (Section 3.4.1.7). This would enable a more quantified model of the specific leaf response of perennial ryegrass to nitrogen supply. The results at LDF also suggest that to determine whether a pasture is nitrogen-limited requires testing of the N content of the pasture and calculation of the NNI, because reliance on the N content alone can be misleading.

‘DairyMod’ was successfully calibrated to simulate pasture growth at LDF, and then applied to the TSD and PF lysimeters. Here, nitrogen deficiency was shown to have again led to sub-optimal herbage accumulation of 12.0 t DM/ha and 14.9 t DM/ha, respectively, over the experimental period (Section 4.3.2.2). However, if the soil N mineralisation rates predicted within the model were too low, the simulated yields could be lower than what was actually grown. Within DairyMod, net N mineralisation was ~150 kg N/ha/y for TSD and ~180 kg N/ha/y for PF. The literature suggests annual gross mineralisation to be 532 kg N/ha/y and 711 kg N/ha/y for Lismore and Templeton silt loam soils in Canterbury, respectively (Mishra et al., 2005). These can be converted to net mineralisation rates. Hatch et al. (2000), for example, found net mineralisation can range from 4-70% of the gross rate for a dairy pasture fertilised with 200 kg N/ha/y. Accordingly, at the reported gross rates, net mineralisation in the two soils could range from 20-500 kg N/ha/y, which covers the simulated rates.

The three commercial dairy farms were representative of typical dairy farm managements across Canterbury. The production results suggest under-fertilisation of pasture to be prevalent across the region. Accordingly, within Canterbury, significant production losses due to under-fertilisation are likely to be common. This is supported in the literature (Easton et al., 2001; Fasi et al., 2008; Horne et al., 2011) where many of the published annual ryegrass yields for Canterbury are well below the maximum of >20 t DM ha⁻¹ (Section 2.3.2.1), which is most probably attributable to N deficiency as well as water deficits.

A consequence of nitrogen deficiency, and therefore sub-optimal herbage accumulation, is a reduced WUE, as observed at each of LDF, TSD and PF (Section 4.3.3.2). The effect of N deficiency was also clearly illustrated in the Lincoln experiment whereby, for the same amount of water used, the +N pastures produced 33-35% more herbage mass than the -N pastures (Section 5.3.6.2). Accordingly,
with increased nitrogen fertiliser, optimal yields could be achieved, without increasing irrigation. Economic gains from doing so could be potentially significant, which have been explored in Section 7.2.4.3.

While DairyMod was found to be effective in the simulation of pasture growth, including herbage production and growth rates, canopy LAI and height under a commercial dairy operation at LDF, limitations within the model were identified. Specifically, the high temperature stress parameter values required in the calibrated model to achieve a close fit between the observed and simulated herbage production at LDF were biologically low (Peri et al., 2002b; White et al., 2008). This led to the temperature response within the model being more limiting than nitrogen availability. Therefore the model failed to simulate a nitrogen response, as described by Grindlay (1997) (Section 2.3.2.4), when the nitrogen fertiliser applied at LDF was doubled, despite the pasture being nitrogen limited. This limitation followed through to Chapter 5 where the calibrated model was unable to represent the leaf area response, and associated changes in herbage yield to nitrogen supply in the Lincoln perennial ryegrass/white clover experiment. However, the ‘correct’ pasture growth predictions were able to be achieved through adjustment of the temperature functions. Accordingly, adjusting the temperature thresholds in DairyMod was found to be a way of compensating for the absence of relationship between nitrogen and leaf extension, and while not the preferred method of achieving a close fit in the data, enabled canopy LAI nad height to be simulated, which was required to test PETc estimation methods.

An update to DairyMod (current version 5.5.0) has been recently released. However, due to the timing of the release relative to this study it was unable to be incorporated into the modelling included in this thesis. The updated model includes a number of new features and some ‘bug fixes’. Adjustments to default parameter values associated with the leaf intake weighting and the effective minimum LAI parameters have been made, and the ability to prescribe fertiliser and irrigation applications by date has been added (Johnson, 2015). These do not address the N response limitation identified, but adjustments to the leaf intake weighting and effective minimum LAI parameters were made to enable more realistic growth characteristics, and therefore may go some way towards improving pasture growth predictions. The introduction of the option to apply N fertiliser and irrigation amounts by date improves DairyMod’s ability to represent actual management scenarios. Re-running the current data sets with the new version would seem a logical first step in determining any improvements in DairyMod.

7.2.2 Quantifying actual evapotranspiration and soil water flow

The total actual evapotranspiration was initially estimated over the experimental period to be 776 mm at TSD, 717 mm at PF and 615 mm at LDF. However, it was identified that without the installation of
rubber rims around the tops of the lysimeters, water redistribution at the surface was possible, and probably elevated the AET calculations at TSD and PF. At LDF, where rims were installed prior to the commencement of the experiment, surface runoff of water was prevented. Using HYDRUS, soil water flow through the soil profile was accurately simulated, and therefore enabled realistic predictions of AET, which reduced the estimates at TSD and PF to 554 mm and 704 mm, respectively. These results therefore highlighted the importance of placing rubber rims around the top of lysimeter casings to ensure all water inputs are fully accounted for, which has not been previously fully understood. This is illustrated by the elevated AET estimates used by Bright (2009a) in the development of a Kc time series for Canterbury, which were later highlighted by Clothier et al. (2009) to have been influenced by surface water redistribution effects.

At LDF and TSD, the maintenance of water at or near field capacity meant that water was not a limiting factor in the pasture growth (Section 4.3.1.2). At PF the soil moisture fell below the critical limiting deficit for approximately a one-week period mid-January 2012 and again for approximately two-weeks from early to mid-February 2012, although the effects on pasture production were estimated to be negligible at ~60 kg DM/ha over the experimental period (Section 4.4.1).

The use of DairyMod and HYDRUS for simulating soil water flow, including profile drainage, soil moisture and surface redistribution of water, were compared and the simulated data from each compared with that observed in the field. Of the two models, HYDRUS was found to be superior. This was in response to the closer predictions of drainage and soil moisture content compared with that observed from the lysimeters and in the Lincoln experiment. The DairyMod soil water flow predictions were also sensitive to the inbuilt temperature stress functions, whereby differences in simulated yield to that observed translated to reduced evapotranspiration estimations and therefore impacted on the soil moisture content and drainage predictions. The DairyMod model also relied on the Penman-Monteith equation for estimating PETc. This is considered the standard method but does not sufficiently account for variations in the canopy under grazing. On the other hand, daily estimations of evaporation and transpiration could be directly input into HYDRUS based on the SWW model predictions, which were found to provide the most accurate predictions when compared with measured AET. Accordingly, HYDRUS soil water flow predictions were not reliant on the successful estimation of canopy growth. Furthermore, the dedicated focus of HYDRUS for simulating soil water flow allowed for the soil properties and soil-water relationships to be represented with greater complexity. Throughout the literature, many examples of the successful use of HYDRUS for simulating soil water dynamics exist (Section 2.3.3.4), and their predictions were comparable in accuracy to those achieved in the current research. However, as has been previously mentioned (Section 4.4.2.1), nothing could be found in the literature comparing actual drainage data with that simulated with
DairyMod to compare the results of this research with, and this provides an avenue for further investigation.

Ideally, a single encompassing model for simulating canopy growth and soil-water-plant relations would be preferable, which DairyMod goes some way towards achieving. However, in addition to the need to more mechanistically account for the canopy response to nitrogen supply, a coupling with HYDRUS and inclusion of the SWW model for the prediction of PETc would largely overcome many of the limitations identified in the current research, and therefore broaden its use within the consulting and research communities.

### 7.2.3 Modelling evapotranspiration

#### 7.2.3.1 Development of a crop coefficient time series

From the measured water use data and estimated PETa, monthly averaged Kc time series were developed for each site (Section 4.3.4). These were then averaged to provide a single mean Kc time series for Canterbury. The monthly site-averaged time series largely fell within the range of Kc values published by Allen et al. (1998) during the irrigation season months, but were consistently below the time series developed for Canterbury by Bright (2009a), which were elevated due to surface run-off effects artificially increasing the apparent water use (Clothier et al., 2009), and a single Kc=1 (Figure 4.19).

Throughout the literature there was a common trend of large spatial and temporal variability in Kc values (Fisher, 2012; Liu & Luo, 2010; Watanabe et al., 2004; Wright, 1982). While attempts have been made to explain the reasons for the variability in the literature, the causes are generally left unanswered, and a mean Kc time series often adopted. However, from the current research it was identified that when daily estimates of water use are used rather than weekly or greater, which were calculated with the SWW model, the spatial variability was largely eliminated, and therefore the time step over which the Kc values were determined was identified as the prevailing cause of the variability. Furthermore, use of a daily time step also led to a clear seasonal trend in the time series, highlighting temporal variability to be in response to seasonal changes, which was expected. When the daily values were averaged to give a monthly time series, averaged across the three lysimeter sites, irrigation season-based estimates of PETc using the time series were comparable to those using the time series developed from the observed lysimeter AET data. In the Lincoln experiment, the two Kc time series (i.e. daily SWW-PETc-based and observed lysimeter AET-based) predicted PETc to be within 5-7% of the AET when water was not limiting. Accordingly, either of the developed time series can be used, with reasonable confidence, to predict PETc of a grazed, fully irrigated perennial ryegrass pasture within Canterbury, over the irrigation season.
7.2.3.2 Evaluation of standard \( \text{PET}_c \) models

Under a rotationally grazed scenario where the pasture conditions deviated from those assumed by the PT, PM\text{FAO} and PM models (i.e. a uniform closed canopy, actively-growing, fully-watered and with no lack of nutrients), accurate predictions could not be achieved, with differences of up to \(~60\%\) from the lysimeter observed AET (Section 4.3.5). With the PM model, there was a strong trend of over-estimation at LAI values greater than \(~1.3\), and under-estimation at lower LAI values. The PT model was also unable to accurately predict water use, which was due to the underlying canopy assumptions encompassed within the empirical coefficient ‘\( \alpha \)’ of the model (Section 2.4.2.2). The PM\text{FAO} method was also found to be inappropriate for estimating \( \text{PET}_c \) from a grazed pasture, as it has been designed to represent the maximum potential evapotranspiration from a uniform closed canopy, without limitations, using climate data only.

However, where the effect of frequent wetting and the influence of a changing canopy on soil exposure, and therefore the evaporation potential from the soil surface were taken into account by using the DCC and SWW models, estimates of AET were within 24\% and 9\% of that measured in the lysimeter experiment, respectively. Confidence in the SWW model was improved when it was validated against AET data in the Lincoln experiment in Chapter 5. The superiority of the SWW model over the DCC model stemmed from its more complex accounting of the canopy and variations under grazing. Specifically, the SWW model is more physically based and works from the ground up to calculate evaporation and transpiration simultaneously, whereas the DCC model takes a more subtractive approach (Section 4.4.5.4).

When SWW-\( \text{PET}_c \) estimations were made using simulated canopy LAI and height data for the lysimeter and Lincoln experiments, annual \( \text{PET}_c \) estimations were within 4 mm/y of that estimated using measured canopy data, indicating that the model was successfully used when observed canopy data were not available but where they were simulated.

Overall, the evapotranspiration modelling highlighted the importance of factoring variations in the canopy into predictions of water use. Separation of evapotranspiration into soil water evaporation and canopy transpiration is also essential, particularly in a grazed system, for predictions to be made accurately and then used with confidence. Accordingly, it was concluded that the pasture canopy forms a connection between the soil and atmosphere, and is an active contributor in the process of evapotranspiration, in terms of both canopy transpiration and its impact on surface evaporation.

7.2.4 Irrigation and nitrogen fertiliser management

7.2.4.1 Irrigation scheduling

The results of the lysimeter research highlighted the issue of over-irrigation and the failure to match irrigation supply to demand. A method of achieving this was identified from the irrigation schedule
modelling in Chapter 6, from which it is recommended that deficit irrigation practices be adopted to allow for more effective use of any rainfall. Irrigation should be applied when the available soil moisture content falls to or below 60% and at a depth that enables effective use of subsequent rainfall inputs (i.e. 10-20 mm). Irrigation should also be delayed by 10-14 days post grazing to avoid unnecessary drainage losses, but only where soil moisture contents permit without compromising herbage production. An implication of this, however, is nitrogen fertiliser is commonly applied immediately after grazing, and irrigation water may be applied to wash the urea in. Accordingly, a delay in irrigation post grazing may not be practical. Alternatively, fertilisation could also be delayed. Another implication is that, in some situations, delaying irrigation by 10-14 days could have adverse implications with regard to pasture production, where the delay leads to limiting soil water conditions. In such situations, irrigation may need to be applied earlier to avoid production losses. However, a deficit approach should still be maintained to prevent unnecessary drainage losses.

The irrigation schedule testing in Chapter 6 quantified the potential for irrigation reduction at the lysimeter sites. Under the proposed optimised irrigation schedule, the actual irrigation applied could have been reduced by 47-64% across the three sites over the 2014/15 irrigation season (until 31 March 2015), without production loss risks. Validation of the proposed optimised irrigation schedule over the 2011/12 lysimeter experiment also identified potential irrigation reductions of up to 65%, while maintaining a similar level of pasture production. However, allowing 40% or greater deficits to develop within the soil profile is not always practical. At LDF, for example, much of the irrigation water was sourced from the Waimakariri Irrigation Scheme (Section 3.2.4.3), where at times restrictions of 25-100% can occur over the irrigation season, depending on river flows (Waimakariri Irrigation Limited, 2013). Accordingly, maintaining soil moisture at or near field capacity may be a conscious or unconscious insurance strategy used by farmers to reduce the severity of any water restrictions on pasture production. Therefore, high supply reliability and the capacity to irrigate on demand would be required for deficit irrigation to be viewed as practical. Furthermore, deficit style irrigation would only be feasible where more intensive soil moisture monitoring or soil water budgeting is conducted across each farm.

Conversely, while minor production losses of up to ~60 kg DM/ha were likely over the 2011/12 lysimeter experiment at PF due to periods where the soil moisture deficit was allowed to be greater than the critical deficit (Section 4.4.1), there was minimal irrigation season drainage. From a water management perspective, this minor loss of production is countered by reduced pumping costs, more efficient water use, and a lower risk of nitrogen leaching, and therefore reduced potential for groundwater contamination. Despite these benefits, pasture optimisation per unit area tends to be the focus rather than maximising the water use efficiency (Section 2.3.2.2) of irrigated pastures (Fereres & Soriano, 2007), and without greater incentive (e.g. financial) it is unlikely to change.
For farms such as LDF where the irrigation, at least in part, is based on scheme supply, irrigation restrictions may limit the opportunity for deficit irrigation. However, where irrigation water is available on demand, as is the case for a majority of consented irrigation across Canterbury, there is the potential for substantial water resource allocation changes. For example, in the most recent water allocation summary released by Ministry for the Environment in 2010, water consented for irrigation in Canterbury totalled 3584 Mm$^3$/y (Rajanayaka et al., 2010). Of this, 55% was sourced from groundwater and the remaining 45% from surface water and storage water resources. Assuming the full 55% of groundwater and 10% of the surface water sourced irrigation was available on demand, and that irrigation of LDF, TSD and PF represented the standard of current industry practice, approximately 746 Mm$^3$/y less irrigation (assuming an average 35% reduction in irrigation requirements) would be required under optimised irrigation scheduling practices. Accordingly, if this were possible, this could reduce pressure on fresh water resources and/or potentially increase irrigation development across the region.

The dominant flow-on effect of reduced irrigation is a reduction in the drainage of water below the root zone. Under the optimised irrigation schedule, the reduction in drainage was estimated to be 53-110 mm or 37-82% from July 2014 to March 2015 at the three lysimeter sites. This was possible as the optimised schedule limited irrigation until a sufficient deficit had been established, such that once irrigation was applied it did not return the soil moisture to field capacity. Rather, subsequent rainfall inputs could be stored by the soil, reducing the potential for drainage. When the optimised irrigation schedule was applied to the 2011/12 lysimeter experimental period, drainage was reduced by 14% (50 mm) and 18% (113 mm) at LDF and TSD, respectively. In contrast, the previous under-irrigation at PF meant that there was an increase in the drainage under the optimised irrigation schedule.

Contrary to what was expected, however, soil surface evaporation losses increased as the return intervals between irrigation events increased. This was due to the irrigation scheduling, in which irrigation was not applied until prescribed soil profile trigger levels had been reached. For the lower irrigation applications, the depth applied was often insufficient to restore the water content in the immediate vicinity of the soil surface above the critical level (Section 2.3.3.4), particularly at the lowest trigger level of 50%. As the irrigation depths applied increased, a higher soil water content was maintained at or near the surface for longer periods of time, increasing evaporation. Overall, however, the effects on evaporation from the irrigation scheduling were small, largely due to the high proportion of evaporation being a response to rainfall rather than irrigation, masking the effects.

7.2.4.2 Fresh water quality implications

While the focus of this research was on water use and therefore water quantity, freshwater quality implications are closely linked and therefore require some mention.
As covered in Chapter 2, irrigation in excess of the soil water holding capacity can increase the potential for nitrate losses to groundwater (Section 2.3.3.1). Accordingly, it was alluded to in Chapter 6 and discussed in Section 7.2.4.1 that a reduction in irrigation water applied has the potential to decrease drainage below the root zone, and therefore carries with it implications for improved groundwater, and ultimately surface water quality.

It was also suggested in Chapter 6 that while irrigation could potentially be reduced without herbage production consequences, to achieve optimal yields, an increase in nitrogen fertilisation across all three dairy farms was required. While the literature clearly highlights that excessive nitrogen fertiliser applications have the potential to increase nitrate leaching to groundwater, this can be avoided if nitrogen is applied during the active growth period, and at rates no greater than the rate of uptake by the plant (Meisinger & Delgado, 2002; Moreno et al., 1996).

7.2.4.3 Practical applications of proposed irrigation and nitrogen managements
From the results of this thesis and the literature, annual Canterbury perennial ryegrass pasture production is in the range of 5-25 t DM/ha/y. Such variability is largely in response to differences in irrigation and nitrogen fertiliser managements. This was illustrated in Chapter 5 and also by Mills (2007) and Black and Murdoch (2013). For example, in Chapter 5, nitrogen increased pasture production by 45% while irrigation increased production by 34%, on average.

In the LDF lysimeter experiment, an average of 10.8 t DM/ha of pasture production was achieved (Chapter 3). The irrigation scheduling results in Chapter 6 and the influence of nitrogen fertilisation in Chapter 5 suggest that at least three different approaches to irrigation and N fertiliser management could be pursued to increase irrigation efficiency and/or achieve maximum herbage production, all of which include either a reduced or removed reliance on irrigation water.

Scenario 1
The first scenario (Scenario 1) involves achieving the same level of pasture production by maintaining the same low level of N fertilisation, but reducing the amount of irrigation water applied through the proposed deficit irrigation practices. Over the 2011/12 experimental period at LDF, for example, with ~50% less irrigation water, the same amount of herbage could have been produced (Table 6.5) when the optimised deficit irrigation methods were applied, as illustrated in Chapter 6.

Scenario 2
The second management scenario (Scenario 2) involves increasing pasture production. This can be achieved by, again, reducing the amount of irrigation water applied but increasing N fertiliser. As with the first management scenario, reducing the amount of irrigation water at LDF by ~50% was possible without adversely affecting pasture production. The necessary N fertiliser to increase pasture production can be estimated.
Based on the pasture at LDF maintaining a herbage N content of ~3% (Section 3.4.1.3), the N uptake by the pasture was ~330 kg N/ha (i.e. 10.8 t DM/ha/y x 0.03), of which 207 kg N/ha was applied in the form of urea (Section 3.2.4.4). The remaining ~123 kg N/ha is assumed to have come from the soil. This is supported by the DairyMod simulated total nitrogen mineralisation at LDF over the experiment of ~130 kg N/ha (not shown). No examples could be found of N mineralisation rates for permanent pasture over a Darnley silt loam soil in the literature. However, annual rates of <100 kg N/ha to ~700 have been reported for a range of silt loam soils under bare ground and pasture throughout the literature (Khumalo, 2012; Mishra et al., 2005; Stark et al., 2007).

The estimated TAGR indicated the pasture at LDF grew at 3.9 kg DM/ha/°Cd (Section 3.3.3), which is less than the maximum 7.5 kg DM/ha/°Cd given in Table 5.11 for a ryegrass pasture. Over the 12 month experimental period, if a growth rate of 5.5 kg DM/ha/°Cd were to be targeted, which is approximately half way between observed 3.9 kg DM/ha/°Cd and maximum 7.5 kg DM/ha/°Cd, production would have increased by approximately a third to 15.3 t DM/ha/y (i.e. 2781 °Cd x 5.5 kg DM/ha/°Cd). At an average herbage N content of 3%, the N required by the pasture would have been ~460 kg N/ha, which suggests an additional 130 kg N/ha (or 63%) would have been required, on the assumption of 100% efficiency of utilisation, in addition to the 207 kg N/ha applied and ~130 kg N/ha that was mineralised. A growth rate of 7.5 kg DM/ha/°Cd would have required a total of 625 kg N/ha (or an additional 295 kg N/ha), and would have resulted in 20.9 t DM/ha/y being produced. The higher herbage yield would have in turn allowed for more production per cow or higher stocking rates, therefore the implications of N leaching would then also need to be considered.

Scenario 3

The final scenario (Scenario 3) involves no irrigation, but an increase in the amount of N fertiliser applied. As illustrated in Chapter 5, ryegrass-based pasture grew at an average annual TAGR of 5.3 kg DM/ha/°Cd over a two-year period (August 2011 – July 2013) (Table 5.11) when 400 kg N/ha were applied, despite water limiting conditions. Applying this growth rate to the LDF Tt of 2781 °Cd gives an estimated production of 14.7 t DM/ha/y. Accordingly, with no irrigation water but a higher nitrogen input, the herbage yield could have been increased by 3.9 t DM/ha/y or 36%. This is largely due to the generally even spread of rainfall throughout the year across Canterbury (Section 3.2.3.1), without which nitrogen uptake from the soil by the canopy may be too severely restricted (Garwood & Sinclair, 1979; Garwood & Williams, 1967). However, this scenario is largely hypothetical, as with irrigation infrastructure in place, it is unlikely it would be left unused by the farmer.
Scenario analysis

The net economic gains from each of the three scenarios can be estimated, based on a simple balance of pasture production financial gains (in the form of milk solids (MS)) minus irrigation pumping, N fertiliser (in the form of urea) costs and an allocation for farm working expenses (FWE) (Table 7.1).

Pumping costs for irrigation can be estimated from the system capacity, the annual water applied and pumping depth, delivery pressure required and efficiency (Neal Borrie, pers. comm., 22 June 2015). These data enable total pumping hours per year to be estimated, and then multiplied by a given electricity cost (cents/kWh) to give an annual per hectare irrigation pumping cost estimate. A system capacity of 0.58 ℓ/s/ha, the equivalent of supplying water at a rate of 5 mm/d, was assumed. As irrigation at LDF was largely supplied by the Waimakariri Irrigation Scheme (Section 3.2.4.3), pumping costs related to the delivery of water under pressure from the farm gate to the irrigation system, for which an assumption of 50 m with a 70% pumping efficiency was made (Neal Borrie, pers. comm., 22 June 2015). The electricity cost was estimated as 0.14 cents/kWh, assuming an ‘anytime’ rate over the summer months (Askin & Askin, 2014).

For the pasture production, ~11 kg DM/ha equates to 1 kg MS/ha (Glassey, 2007). A range of possible milk solid pay-outs from $4.00-$8.00/kg MS was applied. Urea costs ($/ha/y) were estimated based on a purchase value of $605/t (Askin & Askin, 2014). Other farm working expenses were estimated to be $3/kg MS, which is towards to the lower end of what has been surveyed by DairyNZ (DairyNZ, 2014). However, urea and irrigation costs have been separately accounted for in Equation 7.1, and therefore the FWE were reduced accordingly. While FWE do include an allowance for supplementary feed, there is likely to be some disparity between the demand for and on-site production of feed throughout the season under the three scenarios, which has not been accounted for in the estimations. For example, Scenario 3 is likely to lead to an excess in supply during the spring, but during the summer period where soil moisture deficits may be high, herbage production is likely to fall below that required. In such a situation there would be a cost associated with the reallocation of feed throughout the year. Equations 7.2 and 7.3 detail the method used to calculate the net economic gains.

\[
milk\text{ solids (kg MS/ha/y)} = \text{yield (kg DM/ha/y)} \div 11  \tag{7.2}
\]

\[
\text{Estimated gain ($/ha/y)} = \text{milk solids} \times \text{payout} - \text{irrigation pumping} - \text{urea} - \text{FWE}  \tag{7.3}
\]

Table 7.1 indicates that by reducing the amount of irrigation water applied alone, the potential gains were ~$29/ha/y, which equates to ~$11 000/y over the 370 ha property at LDF. By reducing the amount of irrigation water and increasing the amount of N applied to 502 kg/ha/y (equivalent of 1091 kg Urea/ha/y), the economic gains could be up to $4200/ha/y at a pay-out rate of $8.00/kg MS.
However, any such management decision requires an understanding of the potential for nitrate leaching under the various scenarios, and therefore the approach selected is dependent on the outcome of any investigation. This could be achieved through the use of models such as the OVERSEER® nutrient budgets program (Cichota & Snow, 2009), and field validated through the collection and analysis of leachate from the lysimeters when subjected to the range of irrigation and nitrogen fertilisation managements. Overall, however, the reduced drainage under each of the scenarios is likely to offset any potential increases in leaching.

Table 7.1 Estimated net economic gains of three irrigation and nitrogen management scenarios for a range of milk solids pay-outs ($/kg MS) at Larundel Dairy Farm over the 2011/12 experimental period.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Irrigation (mm/y)</th>
<th>N fertiliser (kg N/ha/y)</th>
<th>Herbage yield (t DM/ha/y)</th>
<th>Estimated net gain at given MS pay-out ($/ha/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$4.50</td>
</tr>
<tr>
<td>Actual</td>
<td>225</td>
<td>207</td>
<td>10.8</td>
<td>29</td>
</tr>
<tr>
<td>Scenario 1</td>
<td>120</td>
<td>207</td>
<td>10.8</td>
<td>29</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>120</td>
<td>337</td>
<td>15.3</td>
<td>472</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>120</td>
<td>502</td>
<td>20.9</td>
<td>1018</td>
</tr>
</tbody>
</table>

Note 1: Based on changes in the costs of pumping, N fertiliser and an estimate of farm working expenses and changes in revenue associated with production increases only. Other expenses, for example including soil moisture monitoring and any disparity between the demand for and supply of feed have not been accounted for.

7.3 Conclusions

The research presented in this thesis has provided an in-depth examination of ryegrass pasture evapotranspiration and its relationship with canopy development. Specific conclusions include:

Pasture growth in two of the three lysimeters at LDF was representative of that grown in the wider paddock. Due to nitrogen limiting conditions, pasture production was approximately half the maximum possible for Canterbury. Simulated pasture growth at TSD and PF also identified a lack of nitrogen resulted in limited growth. As the three commercial dairy farms were representative of typical dairy farm managements across Canterbury, it is likely that nitrogen deficiency, and therefore sub-optimal herbage production is common. On average 200 kg N/ha/y were applied across the three farms.

Despite nitrogen limiting conditions, the lysimeter-grown perennial ryegrass pasture at LDF maintained a nitrogen content of ~3%, which equated to a photosynthetic efficiency of ~80%. Accordingly, to establish whether or not a pasture is nitrogen-limited requires testing of the N content of the pasture as well as calculation of the NNI. Reliance on the N content alone can be misleading.
The biophysical pasture model DairyMod successfully simulated pasture growth at LDF. However, DairyMod did not account for the canopy leaf area response to nitrogen availability, and this is a weakness that needs remedying.

Where soil hydraulic property data are available, HYDRUS can be used to simulate soil water flow with reasonable accuracy, and should be used in preference to DairyMod. The DairyMod soil water flow predictions were sensitive to the inbuilt temperature stress functions and did not predict total drainage and soil moisture contents as accurately as HYDRUS. DairyMod could be improved through coupling with HYDRUS and inclusion of the SWW model for the prediction of $\text{PET}_c$, in addition to addressing the leaf area-N response relationship.

Evapotranspiration modelling identified that the canopy forms a pivotal role in the process of evapotranspiration, and therefore its estimation needs to factor in canopy influences including canopy height, leaf area, and ground cover. The PM$_{\text{FAO}}$, PM and PT methods did not sufficiently account for variations in the pasture canopy under a grazed scenario, which led to poor and inconsistent predictions of water use. Overall, the SWW provided the most accurate estimations of water use so is considered the most appropriate method for quantifying evapotranspiration over shorter time periods (i.e. a few days), and could therefore be used for on-farm irrigation management/ scheduling.

Where measured canopy LAI and height data for the pasture canopy are not available when estimating evapotranspiration, DairyMod-simulated estimates can be used to accurately simulate $\text{PET}_c$. However, due to potential errors in the simulated data due to limitations in DairyMod in the simulation of leaf extension, differences in the soil surface evaporation and transpiration components are possible.

The crop coefficient time series developed from actual water use data and the FAO reference crop evapotranspiration can be used to estimate $\text{PET}_c$ over the irrigation season months for a grazed, irrigated perennial ryegrass dairy pasture in Canterbury, and therefore provides a valuable tool for water allocation management in Canterbury.

To avoid over-irrigation, and therefore excess drainage and nitrate leaching losses, deficit irrigation practices should be adopted. Irrigation should only be applied when the available soil moisture content falls to or below 60%, and at a depth that enables effective use of subsequent rainfall inputs (i.e. 10-20 mm). To achieve this, farms should be instrumented with soil moisture sensors as standard practice to aid in irrigation scheduling decisions. Furthermore, irrigation should be delayed by 10-14 days post grazing, where soil moisture conditions allow. However, to achieve maximum production, the amount of nitrogen fertiliser applied may need to be increased, depending on the existing management practices. In general, however, based on the findings of this thesis, the amount of N fertiliser could easily be doubled.
7.4 Recommendations

The results highlighted opportunities for enhancing the experimental design of the research as well as further research opportunities.

7.4.1 Experimental design

At the experimental planning stage for the lysimeter experiment, differences in pasture, irrigation, and grazing management practices among sites were not understood. Rather it was assumed that all sites were fully irrigated and fully fertilised under a rotational grazing system, growing perennial ryegrass/white clover pasture, and as a result pasture canopy measurements were only taken at the LDF site. While DairyMod was able to be used to simulate pasture growth at TSD and PF, once the model was calibrated against data collected at LDF, ideally pasture canopy measurements should have been made at all sites.

Errors in the solar radiation data at the PF and LDF sites (Section 3.2.3) highlighted the importance of ensuring appropriate calibration and performance of instrumentation. Following an investigation by NIWA the faulty instrumentation was replaced. However, had checks on the pyranometer performance been carried out following their installation, the need to correct the measured data could have been avoided.

Neutron probe measurements taken at a depth of 150 mm were used to measure the near surface soil moisture content in the lysimeter experiment. In hindsight, site calibrated TDT or TDR probes should have been installed and used to reduce the potential for error in the near surface soil moisture measurements that can arise due to neutron escape. Despite this, the corrections made to the 150 mm neutron probe measurements based on the post-measurement calibrations of the neutron probe data are considered to have provided sufficiently accurate measurements for the purposes of this study, for which the relative change in soil moisture between measurement dates was the focus.

The lack of rubber rims around the lysimeters at TSD and for part for the lysimeter experiment at PF led to large differences in the observed and simulated data. Had rubber rims been placed around all lysimeters prior to the commencement of the experiment, these differences would have been avoided.

Finally, the design of the lysimeter drainage collection pits meant that flooding of the pit occurred following heavy rainfall and subsequent increases in the groundwater table at LDF (4.2.2.1). Since the experiment, NIWA and Aqualinc Research Ltd have investigated possible options to avoid this in the future and have remedied the problem at LDF through lining the pit floor and walls with concrete.
7.4.2 Future research

The research of this thesis could be extended to explore the possible impacts on freshwater quality from irrigation management practices, which should involve field testing of the proposed optimised irrigation scheduling. There is also the potential for drainage water from the lysimeters to be collected and analysed in support of such research. This was, however, outside the scope of this thesis.

The focus of this study was on water use in Canterbury. Given the success of this research, this could be extended to other regions that are reliant on irrigation to prevent significant soil moisture deficits. In particular, the $K_c$ time series was developed under conditions specific to the Canterbury region, and therefore may not be applicable country-wide, and should therefore be tested.

The research was also focussed on modelling evapotranspiration for perennial ryegrass-based pastures. Extending the research to other grass species or to arable cropping systems, both of which cover extensive areas within New Zealand, would be beneficial.

The response of perennial ryegrass to N supply identified in this research should be validated with results from other experiments. For doing so it is recommended that separation of the pseudostem and leaf nitrogen contents is carried out to enable a more accurate picture of the specific leaf N and leaf N content responses of perennial ryegrass to nitrogen supply.

The results highlight the potential for improvements to the biophysical model DairyMod, which should be investigated. These include investigating the potential to couple the model with HYDRUS to enable more accurate representation of the soil water flow domain, use of the Shuttleworth-Wallace model for the prediction of PETc in place of the Penman-Monteith method, and accounting for the mechanistic relationship between nitrogen and leaf extension, as discussed by Grindlay (1997).
Chapter 8

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## Appendix 1
Darnley silt loam soil profile description for lysimeters 1-3 at Larundel Dairy Farm. Data provided by T. Webb of Landcare Research Ltd.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Top (mm)</th>
<th>Bottom (mm)</th>
<th>Thickness (mm)</th>
<th>Stone (%)</th>
<th>Sand (%)</th>
<th>Clay (%)</th>
<th>Effective depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>180</td>
<td>180</td>
<td>7</td>
<td>5</td>
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<td>220</td>
<td>20</td>
<td>5</td>
<td>25</td>
<td>176</td>
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<tr>
<td>Bt(g)</td>
<td>400</td>
<td>520</td>
<td>120</td>
<td>50</td>
<td>30</td>
<td>33</td>
<td>60</td>
</tr>
<tr>
<td>Bt(g)</td>
<td>520</td>
<td>700</td>
<td>180</td>
<td>50</td>
<td>90</td>
<td>10</td>
<td>90</td>
</tr>
</tbody>
</table>

**Lysimeters 1 (west) and 3 (middle)**

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Top (mm)</th>
<th>Bottom (mm)</th>
<th>Thickness (mm)</th>
<th>Stone (%)</th>
<th>Sand (%)</th>
<th>Clay (%)</th>
<th>Effective depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
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<td>180</td>
<td>180</td>
<td>0</td>
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<td>22</td>
<td>180</td>
</tr>
<tr>
<td>Bw</td>
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<td>270</td>
<td>90</td>
<td>5</td>
<td>10</td>
<td>25</td>
<td>85.5</td>
</tr>
<tr>
<td>Bw</td>
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<td>60.5</td>
</tr>
<tr>
<td>Bt(g)</td>
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<td>550</td>
<td>170</td>
<td>45</td>
<td>60</td>
<td>33</td>
<td>93.5</td>
</tr>
<tr>
<td>BCt(g)</td>
<td>550</td>
<td>700</td>
<td>150</td>
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<td>80</td>
<td>10</td>
<td>60</td>
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## Appendix 2
Lismore stony silt loam soil profile description for lysimeters 1-3 at Three Springs Dairies. Data provided by T. Webb of Landcare Research Ltd.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Top (mm)</th>
<th>Bottom (mm)</th>
<th>Thickness (mm)</th>
<th>Stone (%)</th>
<th>Sand (%)</th>
<th>Clay (%)</th>
<th>Effective depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>280</td>
<td>280</td>
<td>20</td>
<td>10</td>
<td>20</td>
<td>224</td>
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<td>500</td>
<td>220</td>
<td>50</td>
<td>25</td>
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<td>700</td>
<td>200</td>
<td>3</td>
<td>90</td>
<td>80</td>
<td>80</td>
</tr>
</tbody>
</table>

**Lysimeter 1 (east)**

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Top (mm)</th>
<th>Bottom (mm)</th>
<th>Thickness (mm)</th>
<th>Stone (%)</th>
<th>Sand (%)</th>
<th>Clay (%)</th>
<th>Effective depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0</td>
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<td>280</td>
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<td>Bw1</td>
<td>280</td>
<td>400</td>
<td>120</td>
<td>50</td>
<td>25</td>
<td>20</td>
<td>60</td>
</tr>
<tr>
<td>Bw2</td>
<td>400</td>
<td>650</td>
<td>250</td>
<td>60</td>
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<td>80</td>
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<td>BC</td>
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<td>700</td>
<td>50</td>
<td>60</td>
<td>3</td>
<td>90</td>
<td>20</td>
</tr>
</tbody>
</table>

**Lysimeter 2 (middle)**

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Top (mm)</th>
<th>Bottom (mm)</th>
<th>Thickness (mm)</th>
<th>Stone (%)</th>
<th>Sand (%)</th>
<th>Clay (%)</th>
<th>Effective depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>250</td>
<td>250</td>
<td>20</td>
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<td>20</td>
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</tr>
<tr>
<td>Bw1</td>
<td>250</td>
<td>480</td>
<td>230</td>
<td>45</td>
<td>25</td>
<td>20</td>
<td>126.5</td>
</tr>
<tr>
<td>Bw2</td>
<td>480</td>
<td>550</td>
<td>70</td>
<td>60</td>
<td>9</td>
<td>80</td>
<td>28</td>
</tr>
<tr>
<td>BC</td>
<td>550</td>
<td>700</td>
<td>150</td>
<td>50</td>
<td>3</td>
<td>90</td>
<td>75</td>
</tr>
</tbody>
</table>

**Lysimeter 3 (west)**
Appendix 3  Templeton moderately deep silt loam soil profile description for lysimeters 1-3 at Pendo Farms. Data provided by T. Webb of Landcare Research Ltd.

<table>
<thead>
<tr>
<th>Horizon</th>
<th>Top (mm)</th>
<th>Bottom (mm)</th>
<th>Thickness (mm)</th>
<th>Stone (%)</th>
<th>Sand (%)</th>
<th>Clay (%)</th>
<th>Effective layer depth (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lysimeter 1 (east)</strong></td>
<td></td>
<td></td>
<td></td>
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<td>A</td>
<td>0</td>
<td>220</td>
<td>220</td>
<td>0</td>
<td>5</td>
<td>20</td>
<td>220</td>
</tr>
<tr>
<td>Bw1</td>
<td>220</td>
<td>400</td>
<td>180</td>
<td>0</td>
<td>5</td>
<td>20</td>
<td>180</td>
</tr>
<tr>
<td>Bw3</td>
<td>400</td>
<td>700</td>
<td>280</td>
<td>0</td>
<td>5</td>
<td>20</td>
<td>280</td>
</tr>
<tr>
<td><strong>Lysimeter 2 (middle)</strong></td>
<td></td>
<td></td>
<td></td>
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<td>230</td>
<td>290</td>
<td>60</td>
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<td>5</td>
<td>20</td>
<td>60</td>
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<td>400</td>
<td>110</td>
<td>0</td>
<td>5</td>
<td>20</td>
<td>110</td>
</tr>
<tr>
<td>Bw3</td>
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<td>700</td>
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<td>0</td>
<td>5</td>
<td>20</td>
<td>300</td>
</tr>
<tr>
<td><strong>Lysimeter 3 (west)</strong></td>
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<td></td>
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<td>380</td>
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</tr>
<tr>
<td>Bw3</td>
<td>380</td>
<td>700</td>
<td>320</td>
<td>0</td>
<td>5</td>
<td>20</td>
<td>320</td>
</tr>
</tbody>
</table>
Appendix 4  Global radiation data correction at Larundel Dairy Farm and Pendo Farms

The accuracy of the measured radiation data was evaluated using the standard method given by Allen (1996). The method entails a comparison of daily measured pyranometer readings of solar radiation ($R_s$) with calculated short wave radiation expected under clear sky conditions ($R_{so}$). The method is as follows:

$$R_s = K_T R_A$$

where $R_A$ is the extra-terrestrial radiation, which was computed daily as a function of latitude, and the day of the year (Allen et al., 1998). $K_T$ is a clearness index, for which Allen (1996) provides numerous calculation methods. The method used in this study (Equations 4-7 of Allen (1996)) involved calculation of daily $K_T$ as a function of atmospheric pressure and the vapour pressure near the surface, which in turn is a function of the air temperature and relative humidity. The results identified that for TSD the measured daily global radiation values on clear sky days were approximately equal to those expected under clear sky conditions. For LDF and PF peak daily radiation values were approximately 73% and 59% lower, respectively, than what was expected under clear sky conditions (Figure A4a).

The global radiation data measured over the study period were corrected using simple linear regression (Figure A4b). The upper limit values of the measured daily global radiation were regressed against calculated clear sky radiation values at each site. The measured radiation values were corrected (Figure A4c) using the slope and intercept of the regression line as follows:

$$R_{s, \text{adjusted}} = \frac{R_s}{\text{slope}} - \text{intercept}$$

Figure A4a  Comparison of measured daily global radiation ($R_s$) (—) with expected clear sky radiation ($R_{so}$) (---) at Larundel Dairy Farm (LDF) and Pendo Farms (PF).
Figure A4b  Linear regression through upper limit measured daily global radiation values ($R_s$) plotted against calculated daily clear sky radiation values ($R_{so}$) for Larundel Dairy Farm (LDF) and Pendo Farms (PF). Form of the fitted lines are $y = (0.73 \pm 0.006)x + (1.17 \pm 0.102)$ ($r^2 = 0.99$) for LDF and $y = (0.59 \pm 0.005)x - (0.72 \pm 0.098)$ ($r^2 = 0.99$) for PF.

Figure A4c  Comparison of adjusted daily global radiation ($R_{s\_adjusted}$) (—) with expected clear sky radiation ($R_{so}$) (---) at Larundel Dairy Farm (LDF) and Pendo Farms (PF).
Appendix 5  Nash Sutcliffe efficiency (NSE, ○) and normalised root mean square deviation (NRMSD, ●) results of DairyMod sensitivity analysis at Larundel Dairy Farm comparing the effects of including and excluding clover and changing the following from the model default values: pasture rooting depth, low and high temperature (T) stress values and minimum and optimum temperatures for light-saturated leaf gross photosynthesis ($P_m$).
### Appendix 6  Regression equations, standard errors, and coefficients of determination ($r^2$) for the regressions of herbage mass (HM) against compressed plate meter height (RPM), in spring, summer, autumn and winter for ryegrass pasture at Larundel Dairy Farm.

<table>
<thead>
<tr>
<th>Measurement location</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HM vs. RPM</td>
<td>$r^2$</td>
<td>HM vs. RPM</td>
<td>$r^2$</td>
</tr>
<tr>
<td>Cages</td>
<td>$y = 231.7 \pm 11x - 860 \pm 126$</td>
<td>0.97</td>
<td>$y = 160.04 \pm 9.32x - 442.4 \pm 66.1$</td>
<td>0.89</td>
</tr>
<tr>
<td>L1-L3</td>
<td>$y = 195.6 \pm 35.6x - 465 \pm 413$</td>
<td>0.78</td>
<td>$y = 182.1 \pm 45.9x - 511 \pm 340$</td>
<td>0.57</td>
</tr>
<tr>
<td>L2 &amp; L3</td>
<td>$y = 231.9 \pm 37.5x - 631 \pm 439$</td>
<td>0.88</td>
<td>$y = 75.6 \pm 65.1x + 336 \pm 502$</td>
<td>0.05(^1)</td>
</tr>
<tr>
<td>Channels</td>
<td>$y = 213.57 \pm 9.16x - 692 \pm 104$</td>
<td>0.99</td>
<td>$y = 117 \pm 42.1x - 114 \pm 400$</td>
<td>0.38</td>
</tr>
</tbody>
</table>

Note 1: low $r^2$ values due to limited data points

### Appendix 7  Herbage growth rates for individual regrowth cycles of perennial ryegrass pasture for the period 09/09/2011 - 07/09/2012 at Larundel Dairy Farm, West Eyreton, Canterbury.

<table>
<thead>
<tr>
<th>Regrowth cycle</th>
<th>Lysimeters(^1)</th>
<th>Channels</th>
<th>Cages</th>
<th>Site</th>
<th>SEM(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71.9</td>
<td>55.4</td>
<td>79.7</td>
<td>NS</td>
<td>4.8</td>
</tr>
<tr>
<td>2</td>
<td>26.1</td>
<td>30.6</td>
<td>32.1</td>
<td>NS</td>
<td>2.1</td>
</tr>
<tr>
<td>3</td>
<td>37.8</td>
<td>41.6</td>
<td>36.4</td>
<td>NS</td>
<td>1.1</td>
</tr>
<tr>
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<td>53.6</td>
<td>54.1</td>
<td>NS</td>
<td>3.7</td>
</tr>
<tr>
<td>5</td>
<td>38.1</td>
<td>37.8</td>
<td>34.1</td>
<td>NS</td>
<td>2.4</td>
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<tr>
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<td>4.8</td>
<td>6.8</td>
<td>8.0</td>
<td>NS</td>
<td>0.9</td>
</tr>
</tbody>
</table>

Note 1: Treatment means for the lysimeters excluded L1.
Note 2: SEM values show the effects of site. Values in bold are the pooled treatment SEM value when site was not significant.
Appendix 8  Summary of dates and times of missing lysimeter drainage data at Larundel Dairy Farm, Three Springs Dairies and Pendo Farms.

<table>
<thead>
<tr>
<th>Lysimeter site</th>
<th>Start date/time</th>
<th>End date/time</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larundel Dairy Farm</td>
<td>06/11/2011 11:00 a.m.</td>
<td>06/11/2011 11:20 a.m.</td>
<td>20 minutes</td>
</tr>
<tr>
<td></td>
<td>24/12/2011 12:20 a.m.</td>
<td>24/12/2011 12:40 a.m.</td>
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</tr>
<tr>
<td></td>
<td>26/01/2012 09:20 a.m.</td>
<td>27/01/2012 09:00 a.m.</td>
<td>20 minutes</td>
</tr>
<tr>
<td></td>
<td>02/03/2012 07:40 a.m.</td>
<td>02/03/2012 08:00 a.m.</td>
<td>20 minutes</td>
</tr>
<tr>
<td></td>
<td>15/04/2012 10:20 a.m.</td>
<td>15/04/2012 10:40 a.m.</td>
<td>20 minutes</td>
</tr>
<tr>
<td></td>
<td>04/06/2012 05:00 p.m.</td>
<td>04/06/2012 08:00 p.m.</td>
<td>3 hours</td>
</tr>
<tr>
<td></td>
<td>05/06/2012 07:00 a.m.</td>
<td>05/06/2012 08:00 a.m.</td>
<td>1 hour</td>
</tr>
<tr>
<td></td>
<td>28/06/2012 09:00 a.m.</td>
<td>29/06/2012 11:50 a.m.</td>
<td>26 hours, 50 minutes</td>
</tr>
<tr>
<td></td>
<td>03/07/2012 11:40 a.m.</td>
<td>03/07/2012 01:00 p.m.</td>
<td>1 hour, 20 minutes</td>
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<tr>
<td></td>
<td>13/08/2012 11:50 p.m.</td>
<td>15/09/2012 00:00 a.m.</td>
<td>&gt;1 month</td>
</tr>
<tr>
<td>Three Springs Dairies</td>
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<td>1 hour</td>
</tr>
<tr>
<td></td>
<td>06/09/2011 04:00 p.m.</td>
<td>06/09/2011 05:00 p.m.</td>
<td>1 hour</td>
</tr>
<tr>
<td></td>
<td>04/06/2012 05:00 p.m.</td>
<td>04/06/2012 08:00 p.m.</td>
<td>3 hours</td>
</tr>
<tr>
<td></td>
<td>05/06/2012 07:00 a.m.</td>
<td>05/06/2012 08:00 a.m.</td>
<td>1 hour</td>
</tr>
<tr>
<td></td>
<td>03/07/2012 12:00 p.m.</td>
<td>03/07/2012 01:00 p.m.</td>
<td>1 hour</td>
</tr>
<tr>
<td>Pendo Farms</td>
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<td>01/09/2011 03:00 p.m.</td>
<td>1 hour</td>
</tr>
<tr>
<td></td>
<td>06/09/2011 04:00 p.m.</td>
<td>06/09/2011 05:00 p.m.</td>
<td>1 hour</td>
</tr>
<tr>
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<td>04/06/2012 05:00 p.m.</td>
<td>04/06/2012 07:00 p.m.</td>
<td>2 hours</td>
</tr>
<tr>
<td></td>
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<td>05/06/2012 08:00 a.m.</td>
<td>2 hours</td>
</tr>
<tr>
<td></td>
<td>27/06/2012 09:00 a.m.</td>
<td>28/06/2012 10:50 a.m.</td>
<td>26 hours, 50 minutes</td>
</tr>
<tr>
<td></td>
<td>29/06/2012 11:00 a.m.</td>
<td>30/06/2012 02:50 p.m.</td>
<td>27 hours, 50 minutes</td>
</tr>
<tr>
<td></td>
<td>03/07/2012 11:00 a.m.</td>
<td>03/07/2012 01:00 p.m.</td>
<td>2 hours</td>
</tr>
</tbody>
</table>

Appendix 9  Gravimetric-based measurements of the volumetric water content (v%) against HydroSense measured volumetric water content (v%) for the upper 120 mm field soil profile at Larundel Dairy Farm (LDF) (A), Three Springs Dairies (TSD) (B), and Pendo Farms (PF) (C). Forms of the fitted lines are $y = (0.76\pm 0.071)x + (16.64\pm2.040) \ (r^2=0.91)$ for LDF, $y = (0.78\pm 0.112)x + (12.69\pm3.820) \ (r^2=0.84)$ for TSD, and $y = (0.94\pm 0.078)x + (10.82\pm2.000) \ (r^2=0.93)$ for PF. 1:1 line shown for illustrative purposes (- - -)
Appendix 10  Calibrated Hydrosense probe estimates of the volumetric water content (v%) against neutron probe measured volumetric water content (%) for the upper 120 mm lysimeter soil profiles at Larundel Dairy Farm (LDF) (a), Three Springs Dairies (TSD) (b), and Pendo Farms (PF) (c). The fitted lines were forced through the origin due to irrigation preventing measurements at lower soil water contents. It is reasonable to expect that at a moisture content of zero, the neutron probe should also give a reading of zero. Forms of the fitted lines when forced through the origin are $y = (0.93 \pm 0.009)x \ (r^2=0.60)$ for LDF, $y = (1.03 \pm 0.036)x \ (r^2=0.48)$ for TSD, and $y = (1.18 \pm 0.051)x \ (r^2=0.40)$ for PF. 1:1 line shown for illustrative purposes (---).

Appendix 11  Estimated soil moisture retention characteristic curves for soil profile layers 0-180 mm (——), 180-520 mm (---) and 520-700 mm (---) derived from soil hydraulic parameters in Table 4.1 for a Darnley Silt Loam soil, adjusted for stone content, West Eyreton, Canterbury.
Appendix 12  Nash Sutcliffe efficiency (NSE, ○) and normalised root mean square deviation (NRMSD, ●) results of HYDRUS sensitivity analysis at Larundel Dairy Farm comparing the effects of changing the following from the model default values: pasture rooting depth; ‘I’ and $K_{sat}$ soil hydraulic parameters; the allowed surface ponding depth; and plant root water uptake parameters $h_1$ (soil water pressure head at saturation), $h_4$ (the pressure head at the wilting point), $h_2$ and $h_3$ (the soil water pressure heads between which water uptake is maximal) and the potential transpiration rates ($T_{high}$ and $T_{low}$), which vary with $h_3$. 
Appendix 13  Soil hydraulic property and textural data, adjusted for stone content, for a Lismore silt loam soil at Three Springs Dairies, Methven, Canterbury from Dr Rogerio Cichota (pers. comm., 19 Dec. 2014). $\theta_r$, $\theta_s$, $\theta_{FC}$, and $\theta_{WP}$ are the residual, saturated, field capacity and wilting point volumetric soil water contents, $K_{sat}$ is the saturated hydraulic conductivity and $\Psi$ is the air entry water suction. $b$ is a fitting constant used by Brooks and Corey (1964).

<table>
<thead>
<tr>
<th>Soil depth (mm)</th>
<th>$\theta_r$ %</th>
<th>$\theta_s$ %</th>
<th>$\theta_{FC}$ ($\theta_{10}$ kPa) %</th>
<th>$\theta_{WP}$ ($\theta_{10}$ kPa) %</th>
<th>$K_{sat}$ mm/d</th>
<th>$\Psi$ (kPa)</th>
<th>b -</th>
<th>Stones %</th>
<th>Sand %</th>
<th>Silt %</th>
<th>Clay %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-100</td>
<td>3.3</td>
<td>39.4</td>
<td>33.2</td>
<td>15.8</td>
<td>10656</td>
<td>-1.2</td>
<td>6.12</td>
<td>17.0</td>
<td>27.0</td>
<td>45.0</td>
<td>28.0</td>
</tr>
<tr>
<td>100-300</td>
<td>3.0</td>
<td>34.5</td>
<td>27.4</td>
<td>13.3</td>
<td>3091</td>
<td>-3.1</td>
<td>5.61</td>
<td>26.0</td>
<td>25.0</td>
<td>49.0</td>
<td>27.0</td>
</tr>
<tr>
<td>300-500</td>
<td>1.8</td>
<td>30.8</td>
<td>16.6</td>
<td>6.9</td>
<td>2342</td>
<td>-2.8</td>
<td>4.86</td>
<td>54.0</td>
<td>33.0</td>
<td>43.0</td>
<td>25.0</td>
</tr>
<tr>
<td>500-700</td>
<td>3.6</td>
<td>14.7</td>
<td>9.0</td>
<td>4.3</td>
<td>12103</td>
<td>-1.4</td>
<td>2.26</td>
<td>64.0</td>
<td>70.0</td>
<td>18.0</td>
<td>13.0</td>
</tr>
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</table>
Appendix 14  Estimated soil moisture retention characteristic curves for soil profile layers 0-100 mm (---), 100-300 mm (- - -), 300-500 mm (---) and 500-700 (···) derived from soil hydraulic parameters in Table 4.4 for a Lismore stony silt loam soil at Three Springs Dairies, Methven, Canterbury.
Appendix 15  Soil water content (%) at varying matric potentials and saturated hydraulic conductivity values for a Templeton silt loam soil, Canterbury. (a)-(c) present data sourced from Watt and Burgham (1992) and (d) data from (Fraser, 1992). Soil depths in brackets are the assumed soil layer depth where data is not provided in the literature for the full soil profile.

(a)  **Watt and Burgham (1992): Templeton deep silt loam on sand (1)**

<table>
<thead>
<tr>
<th>Matric potential (kPa)</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-4</th>
<th>-5</th>
<th>-10</th>
<th>-20</th>
<th>-50</th>
<th>-100</th>
<th>-329</th>
<th>-882</th>
<th>-1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.220</td>
<td>0.572</td>
<td>0.400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>221-350</td>
<td>0.516</td>
<td>0.450</td>
<td>0.322</td>
<td>0.233</td>
<td>0.200</td>
<td>0.150</td>
<td>0.101</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>670-700 (351-700)</td>
<td>0.482</td>
<td>0.400</td>
<td>0.281</td>
<td>0.178</td>
<td>0.105</td>
<td>0.078</td>
<td>0.039</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

(b)  **Watt and Burgham (1992): Templeton deep silt loam on sand (2)**

<table>
<thead>
<tr>
<th>Matric potential (kPa)</th>
<th>0</th>
<th>-0.2</th>
<th>-2</th>
<th>-5</th>
<th>-10</th>
<th>-20</th>
<th>-50</th>
<th>-100</th>
<th>-264</th>
<th>-302</th>
<th>-590</th>
<th>-839</th>
<th>-1251</th>
<th>-1500</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.220</td>
<td>0.477</td>
<td>0.400</td>
<td>0.369</td>
<td>0.349</td>
<td>0.326</td>
<td>0.301</td>
<td>0.270</td>
<td>0.250</td>
<td>0.200</td>
<td>0.200</td>
<td>0.156</td>
<td>5352</td>
<td></td>
<td></td>
</tr>
<tr>
<td>290-340 (221-340)</td>
<td>0.438</td>
<td>0.321</td>
<td>0.304</td>
<td>0.287</td>
<td>0.264</td>
<td>0.238</td>
<td>0.200</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.159</td>
<td>336</td>
<td></td>
</tr>
<tr>
<td>560-700 (341-700)</td>
<td>0.445</td>
<td>0.400</td>
<td>0.369</td>
<td>0.350</td>
<td>0.336</td>
<td>0.326</td>
<td>0.220</td>
<td>0.200</td>
<td></td>
<td></td>
<td></td>
<td>0.150</td>
<td>0.139</td>
<td>26.4</td>
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</tbody>
</table>

(c)  **Watt and Burgham (1992): Templeton deep silt loam on sand (3)**

<table>
<thead>
<tr>
<th>Matric potential (kPa)</th>
<th>0</th>
<th>-1</th>
<th>-2</th>
<th>-5</th>
<th>-10</th>
<th>-20</th>
<th>-50</th>
<th>-100</th>
<th>-227</th>
<th>-541</th>
<th>-861</th>
<th>-1035</th>
<th>-1500</th>
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<tbody>
<tr>
<td>0.190</td>
<td>0.454</td>
<td>0.400</td>
<td>0.378</td>
<td>0.361</td>
<td>0.348</td>
<td>0.334</td>
<td>0.318</td>
<td>0.250</td>
<td></td>
<td></td>
<td></td>
<td>0.200</td>
<td>0.158</td>
</tr>
<tr>
<td>340-500 (191-500)</td>
<td>0.382</td>
<td>0.350</td>
<td>0.325</td>
<td>0.309</td>
<td>0.297</td>
<td>0.284</td>
<td>0.269</td>
<td>0.250</td>
<td></td>
<td></td>
<td>0.2</td>
<td>0.162</td>
<td>24</td>
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</table>
(d) Fraser (1992): Templeton deep silt loam

<table>
<thead>
<tr>
<th>Soil depth</th>
<th>Matric potential (kPa)</th>
<th>K\text{sat} (mm/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>0-250</td>
<td>0.467</td>
<td>0.409</td>
</tr>
<tr>
<td>251-450</td>
<td>0.423</td>
<td>0.351</td>
</tr>
<tr>
<td>451-600</td>
<td>0.583</td>
<td>0.545</td>
</tr>
<tr>
<td>601-700</td>
<td>0.585</td>
<td>0.551</td>
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</table>
Appendix 16  Estimated soil moisture retention characteristic curves for soil profile layers 0-220 mm (—), 290-340 mm (- -) and 560-700 mm (---) derived from soil hydraulic parameters in Table 4.5 for the Templeton deep silt loam (2) soil in Canterbury given by Watt and Burgham (1992).
Appendix 17 Monthly averaged mean daily actual evapotranspiration (AET\textsubscript{daily}) for perennial ryegrass pastures at Larundel Dairy Farm (LDF), Three Springs Dairies (TSD) and Pendo Farms (PF). AET\textsubscript{daily} calculated using measured drainage data and then using drainage data modelled with HYDRUS-1D for PF prior to rubber rim installation and for TSD. SEM values in bold are the pooled treatment SEM value where the effect of site was not significant. Treatment means across each row followed by the same subscript letter were similar.

<table>
<thead>
<tr>
<th>Month</th>
<th>LDF</th>
<th>TSD</th>
<th>PF</th>
<th>Site</th>
<th>SEM</th>
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<td><strong>AET with measured drainage</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep-11</td>
<td>1.35\textsubscript{b}</td>
<td>1.72\textsubscript{a}</td>
<td>1.99\textsubscript{a}</td>
<td>0.019</td>
<td>0.091</td>
</tr>
<tr>
<td>Oct-11</td>
<td>2.03\textsubscript{a}</td>
<td>2.42\textsubscript{a}</td>
<td>2.54\textsubscript{a}</td>
<td>NS</td>
<td>0.110</td>
</tr>
<tr>
<td>Nov-11</td>
<td>2.55\textsubscript{b}</td>
<td>3.05\textsubscript{b}</td>
<td>3.64\textsubscript{a}</td>
<td>0.013</td>
<td>0.137</td>
</tr>
<tr>
<td>Dec-11</td>
<td>2.95\textsubscript{b}</td>
<td>4.07\textsubscript{a}</td>
<td>3.5\textsubscript{b}</td>
<td>0.013</td>
<td>0.142</td>
</tr>
<tr>
<td>Jan-12</td>
<td>3.03\textsubscript{a}</td>
<td>3.87\textsubscript{a}</td>
<td>3.71\textsubscript{a}</td>
<td>NS</td>
<td>0.160</td>
</tr>
<tr>
<td>Feb-12</td>
<td>2.4\textsubscript{a}</td>
<td>2.95\textsubscript{a}</td>
<td>1.9\textsubscript{a}</td>
<td>NS</td>
<td>0.207</td>
</tr>
<tr>
<td>Mar-12</td>
<td>1.72\textsubscript{b}</td>
<td>2.12\textsubscript{a}</td>
<td>2.16\textsubscript{a}</td>
<td>0.028</td>
<td>0.078</td>
</tr>
<tr>
<td>Apr-12</td>
<td>1.16\textsubscript{a}</td>
<td>1.52\textsubscript{a}</td>
<td>1.17\textsubscript{b}</td>
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<td>0.048</td>
</tr>
<tr>
<td>May-12</td>
<td>1.12\textsubscript{a}</td>
<td>0.77\textsubscript{b}</td>
<td>0.65\textsubscript{b}</td>
<td>0.031</td>
<td>0.081</td>
</tr>
<tr>
<td>Jun-12</td>
<td>0.79\textsubscript{a}</td>
<td>0.54\textsubscript{a}</td>
<td>0.96\textsubscript{a}</td>
<td>NS</td>
<td>0.102</td>
</tr>
<tr>
<td>Jul-12</td>
<td>0.48\textsubscript{a}</td>
<td>0.57\textsubscript{a}</td>
<td>0.49\textsubscript{a}</td>
<td>NS</td>
<td>0.102</td>
</tr>
<tr>
<td>Aug-12</td>
<td>0.54\textsubscript{a}</td>
<td>1.68\textsubscript{a}</td>
<td>0.47\textsubscript{a}</td>
<td>0.037</td>
<td>0.234</td>
</tr>
<tr>
<td>Sep-12</td>
<td>0.81\textsubscript{b}</td>
<td>1.11\textsubscript{ab}</td>
<td>1.55\textsubscript{a}</td>
<td>0.039</td>
<td>0.131</td>
</tr>
<tr>
<td><strong>AET with potential drainage (TSD and PF)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sep-11</td>
<td>1.35\textsubscript{b}</td>
<td>1.37\textsubscript{b}</td>
<td>1.95\textsubscript{o}</td>
<td>0.004</td>
<td>0.065</td>
</tr>
<tr>
<td>Oct-11</td>
<td>2.03\textsubscript{a}</td>
<td>1.65\textsubscript{a}</td>
<td>2.24\textsubscript{o}</td>
<td>NS</td>
<td>0.109</td>
</tr>
<tr>
<td>Nov-11</td>
<td>2.55\textsubscript{b}</td>
<td>2.53\textsubscript{o}</td>
<td>3.55\textsubscript{a}</td>
<td>0.004</td>
<td>0.103</td>
</tr>
<tr>
<td>Dec-11</td>
<td>2.95\textsubscript{o}</td>
<td>3.2\textsubscript{a}</td>
<td>3.5\textsubscript{o}</td>
<td>NS</td>
<td>0.111</td>
</tr>
<tr>
<td>Jan-12</td>
<td>3.03\textsubscript{b}</td>
<td>2.99\textsubscript{b}</td>
<td>3.71\textsubscript{o}</td>
<td>&lt;0.001</td>
<td>0.047</td>
</tr>
<tr>
<td>Feb-12</td>
<td>2.4\textsubscript{a}</td>
<td>2.12\textsubscript{ab}</td>
<td>1.9\textsubscript{b}</td>
<td>0.029</td>
<td>0.079</td>
</tr>
<tr>
<td>Mar-12</td>
<td>1.72\textsubscript{o}</td>
<td>1.77\textsubscript{o}</td>
<td>2.16\textsubscript{a}</td>
<td>NS</td>
<td>0.087</td>
</tr>
<tr>
<td>Apr-12</td>
<td>1.16\textsubscript{o}</td>
<td>1.24\textsubscript{o}</td>
<td>1.17\textsubscript{o}</td>
<td>NS</td>
<td>0.023</td>
</tr>
<tr>
<td>May-12</td>
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<td>0.16\textsubscript{o}</td>
<td>0.65\textsubscript{o}</td>
<td>0.002</td>
<td>0.073</td>
</tr>
<tr>
<td>Jun-12</td>
<td>0.79\textsubscript{o}</td>
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<td>0.96\textsubscript{o}</td>
<td>0.011</td>
<td>0.106</td>
</tr>
<tr>
<td>Jul-12</td>
<td>0.48\textsubscript{o}</td>
<td>0.07\textsubscript{o}</td>
<td>0.49\textsubscript{o}</td>
<td>NS</td>
<td>0.106</td>
</tr>
<tr>
<td>Aug-12</td>
<td>0.54\textsubscript{o}</td>
<td>0.69\textsubscript{o}</td>
<td>0.47\textsubscript{o}</td>
<td>NS</td>
<td>0.087</td>
</tr>
<tr>
<td>Sep-12</td>
<td>0.81\textsubscript{b}</td>
<td>1.13\textsubscript{ab}</td>
<td>1.55\textsubscript{o}</td>
<td>0.040</td>
<td>0.132</td>
</tr>
</tbody>
</table>
Appendix 18  Daily DairyMod-simulated potential evapotranspiration (DMod-PET\textsubscript{c}) and daily actual evapotranspiration (AET\textsubscript{daily}) from lysimeter-grown perennial ryegrass/white clover pastures at Larundel Dairy Farm (▲,—) (LDF), Three Springs Dairies (◆,—) (TSD) and Pendo Farms (●,—) (PF), for the period 07/09/2011-14/09/2012. TSD (◇,—) and PF (○,—) also compare DMod-PET\textsubscript{c} with AET\textsubscript{daily} calculated with the estimated potential drainage data from Figure 4.13. Plots compare the relationship between AET\textsubscript{daily} and DMod-PET\textsubscript{c} (top), and residuals (DMod-PET\textsubscript{c} - AET\textsubscript{daily}) over time (bottom). Forms of the fitted lines (---) are: (a) y = (0.7340±0.03)x + 0.50±0.05 (r\textsuperscript{2}=0.68), (b(i)) y = (1.30±0.04)x + 0.29±0.07 (r\textsuperscript{2}=0.71), (b(ii)) y = (1.12±0.03)x - 0.05±0.06 (r\textsuperscript{2}=0.74), (c(i)) y = (0.89±0.03)x + 0.47±0.07 (r\textsuperscript{2}=0.67) and (c(ii)) y = (0.88±0.03)x + 0.46±0.07 (r\textsuperscript{2}=0.67).
Appendix 19  Daily Priestley-Taylor potential evapotranspiration (PT-PET_c) and daily actual evapotranspiration (AET_daily) from lysimeter-grown perennial ryegrass/white clover pastures at Larundel Dairy Farm (▲, —) (LDF), Three Springs Dairies (◆, —) (TSD) and Pendo Farms (●, —) (PF), for the period 07/09/2011-14/09/2012. TSD (◇, —) and PF (○, —) also compare PT-PET_c with AET_daily calculated with the estimated potential drainage data from Figure 4.13. Plots compare the relationship between AET_daily and PT-PET_c (top), and residuals (PT-PET_c - AET_daily) over time (bottom). Forms of the fitted lines (---) are: (a) \( y = (0.56±0.01)x + 0.43±0.04 \) \( (r^2=0.83) \), (b(i)) \( y = (0.85±0.02)x + 0.41±0.05 \) \( (r^2=0.83) \), (b(ii)) \( y = (0.75±0.01)x + 0.04±0.03 \) \( (r^2=0.89) \), (c(i)) \( y = (0.720±0.02)x + 0.35±0.05 \) \( (r^2=0.81) \) and (c(ii)) \( y = (0.71±0.02)x + 0.34±0.05 \) \( (r^2=0.81) \).
Appendix 20  Daily FAO modified Penman-Monteith reference crop potential evapotranspiration (FAO-PET<sub>c</sub>) and daily actual evapotranspiration (AET<sub>daily</sub>) from lysimeter-grown perennial ryegrass/white clover pastures at Larundel Dairy Farm (▲,---) (LDF), Three Springs Dairies (◆,---) (TSD) and Pendo Farms (●,---) (PF), for the period 07/09/2011-14/09/2012. TSD (◇,—) and PF (○,—) also compare FAO-PET<sub>c</sub> with AET<sub>daily</sub> calculated with the estimated potential drainage data from Figure 4.13. Plots compare the relationship between AET<sub>daily</sub> and FAO-PET<sub>c</sub> (top), and residuals (FAO-PET<sub>c</sub> - AET<sub>daily</sub>) over time (bottom). Forms of the fitted lines (---) are: (a) y= (0.71±0.01)x - 0.05±0.03 (r<sup>2</sup>=0.92), (b(i)) y= (0.98±0.01)x - 0.23±0.05 (r<sup>2</sup>=0.90), (b(ii)) y= (0.83±0.01)x - 0.47±0.04 (r<sup>2</sup>=0.91), (c(i)) y= (0.86±0.01)x - 0.20±0.03 (r<sup>2</sup>=0.940) and (c(ii)) y= (0.85±0.01)x - 0.20±0.03 (r<sup>2</sup>=0.95).
Appendix 21  Daily Penman-Monteith potential evapotranspiration (PM-PET) and daily actual evapotranspiration (AET\textsubscript{daily}) from lysimeter-grown perennial ryegrass/white clover pastures at Larundel Dairy Farm (▲, —) (LDF), Three Springs Dairies (◆, —) (TSD) and Pendo Farms (○, —) (PF), for the period 07/09/2011-14/09/2012. TSD (◇, —) and PF (○, —) also compare PM-PET\textsubscript{c} with AET\textsubscript{daily} calculated with the estimated potential drainage data from Figure 4.13. Plots compare the relationship between AET\textsubscript{daily} and PM-PET\textsubscript{c} (top), and residuals (PM-PET\textsubscript{c} - AET\textsubscript{daily}) over time (bottom). Forms of the fitted lines (---) are: (a) \( y = (0.67\pm0.02)x + 0.22\pm0.04 \) \( r^2=0.82 \), (b(i)) \( y = (1.15\pm0.03)x - 0.09\pm0.06 \) \( r^2=0.84 \), (b(ii)) \( y = (0.99\pm0.02)x - 0.38\pm0.04 \) \( r^2=0.88 \), (c(i)) \( y = (0.95\pm0.02)x - 0.01\pm0.06 \) \( r^2=0.82 \) and (c(ii)) \( y = (0.94\pm0.02)x - 0.02\pm0.05 \) \( r^2=0.82 \).
Appendix 22  Daily dual crop coefficient potential evapotranspiration (DCC-PET\textsubscript{c}) and daily actual evapotranspiration (AET\textsubscript{daily}) from lysimeter-grown perennial ryegrass/white clover pastures at Larundel Dairy Farm (▲, −) (LDF), Three Springs Dairies (◆, −) (TSD) and Pendo Farms (●, −) (PF), for the period 07/09/2011-14/09/2012. TSD (◇, −) and PF (○, −) also compare DCC-PET\textsubscript{c} with AET\textsubscript{daily} calculated with the estimated potential drainage data from Figure 4.13. Plots compare the relationship between AET\textsubscript{daily} and DCC-PET\textsubscript{c} (top), and residuals (DCC-PET\textsubscript{c} - AET\textsubscript{daily}) over time (bottom). Forms of the fitted lines (---) are: (a) $y = (0.73 \pm 0.02)x + 0.39 \pm 0.05$ ($r^2=0.74$), (b(i)) $y = (0.96 \pm 0.03)x + 0.29 \pm 0.06$ ($r^2=0.78$), (b(ii)) $y = (0.81 \pm 0.02)x - 0.01 \pm 0.05$ ($r^2=0.78$), (c(i)) $y = (0.88 \pm 0.02)x + 0.24 \pm 0.04$ ($r^2=0.88$) and (c(ii)) $y = (0.87 \pm 0.02)x + 0.23 \pm 0.04$ ($r^2=0.88$).
Appendix 23  Mean daily residuals of dual crop coefficient modelled potential evapotranspiration (DCC-PETc) minus lysimeter measured actual evapotranspiration (AET) for each measurement time step for the period 07/09/2011-14/09/2012, at Larundel Dairy Farm (▲), Three Springs Dairies (●, ◇) and Pendo Farms (●, ○). Closed symbols correspond to AETd calculations with measured drainage data. Open symbols correspond to AETd calculations with the estimated potential drainage data from Figure 4.10. Each measurement time step refers to the period between consecutive soil moisture measurements, over which lysimeter AET was calculated.
Appendix 24  Daily Shuttleworth-Wallace potential evapotranspiration (SWW-PET\textsubscript{c}) and daily actual evapotranspiration (AET\textsubscript{daily}) from lysimeter-grown perennial ryegrass/white clover pastures at Larundel Dairy Farm (▲, —) (LDF), Three Springs Dairies (◆, —) (TSD) and Pendo Farms (●, —) (PF), for the period 07/09/2011-14/09/2012. TSD (◇, —) and PF (○, —) also compare SWW-PET\textsubscript{c} with AET\textsubscript{daily} calculated with the estimated potential drainage data from Figure 4.13. Plots compare the relationship between AET\textsubscript{daily} and SWW-PET\textsubscript{c} (top), and residuals (SWW-PET\textsubscript{c} - AET\textsubscript{daily}) over time (bottom). Forms of the fitted lines (---) are: (a) $y = (0.77 \pm 0.02)x + 0.41 \pm 0.04$ ($r^2 = 0.83$), (b(i)) $y = (1.13 \pm 0.03)x + 0.39 \pm 0.05$ ($r^2 = 0.83$), (b(ii)) $y = (0.99 \pm 0.02)x + 0.03 \pm 0.03$ ($r^2 = 0.88$), (c(i)) $y = (0.91 \pm 0.03)x + 0.36 \pm 0.05$ ($r^2 = 0.78$) and (c(ii)) $y = (0.90 \pm 0.02)x + 0.35 \pm 0.05$ ($r^2 = 0.78$).
Appendix 25  Estimated soil moisture retention characteristic curves for layers 0-180 mm (—), 180-360 mm (---) and 360-500 mm (---) derived from modified soil hydraulic parameters in Table 5.10 for a Wakanui Silt loam at Lincoln, Canterbury.
Appendix 26  Nash Sutcliffe efficiency (NSE, ○) and normalised root mean square deviation (NRMSD, ●) results of HYDRUS site specific soil hydraulic parameter testing at Iversen Field, Lincoln University for the +I+N treatments. The analysis compared the effects of adjusting the estimated soil hydraulic parameters $\theta_r$ (residual water content), $\theta_s$ (saturated water content), n and $\alpha$ (soil water retention function parameters), $K_{sat}$ (saturated hydraulic conductivity) and $I$ (tortuosity parameter) from Table 5.9.
Appendix 27  Observed herbage yield (kg DM/ha) of individual regrowth cycles of perennial ryegrass/white clover pasture at Iversen Field block I8 at Lincoln University, Canterbury. Treatments are irrigated (+I) or unirrigated (-I), nitrogen-fertilised (+N) or unfertilised (-N). Treatment means across each row followed by the same subscript letter were similar.

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Appendix 28  Observed nitrogen content (%) of individual regrowth cycles of perennial ryegrass/white clover pasture at Iversen Field block I8 at Lincoln University, Canterbury. Treatments are irrigated (+I) or unirrigated (-I), nitrogen-fertilised (+N) or unfertilised (-N). SEM values in bold are the pooled treatment SEM value where the effects of I or N were not significant. Treatment means across each row followed by the same subscript letter were similar.

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Appendix 29  HYDRUS-simulated drainage (mm) below 900 mm for individual regrowth cycles from perennial ryegrass/white clover pasture at Iversen Field block I8, Lincoln University, Canterbury. Treatments are irrigated (+I) or unirrigated (-I), nitrogen-fertilised (+N) or unfertilised (-N). Treatment means across each row followed by the same subscript letter were similar.

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Appendix 30  Calculation of the potential evapotranspiration deficit (PED) (Mullan et al., 2005)

The water balance calculation used to determine PED assumes that the water gains and losses to the soil profile are typically in balance. Provided water is non-limiting, the balance for a given rainfall period can be written:

\[ P = PET_0 + RO + D \pm \Delta S \]

Where \( P \) is precipitation, \( PET_0 \) is the potential (or upper limit) climate-derived evapotranspiration for pasture, \( RO \) is surface runoff, \( D \) is drainage, and \( \Delta S \) is the change in water storage. In principle, for each day,

\[ S = S_{d-1} + P - PET - RO - D \]

where \( S \) is the new storage, and \( S_{d-1} \) is the water storage for the previous day.

The available water capacity (AWC) for the soil is taken to be the difference in the soil water storage between field capacity and wilting point. Rainfall in excess of field capacity is assumed lost to the water balance by runoff and drainage.

If:

\[ S_{d-1} + P - PET_0 > AWC \]

Then:

\[ (S_{d-1} + P - PET_0) - AWC = (RO + D) \]

As \( S \) is reduced and water extraction by the plant becomes increasingly difficult, constrained water use is estimated assuming evapotranspiration (ET) continues at its potential rate until half AWC is depleted, following which it ceases until further rain occurs.

If:

\[ S < \frac{1}{2}(AWC) \]

Then:

\[ ET = 0 \]

The difference between the subsequent soil water-restricted evapotranspiration, (RET), and the atmospheric potential evapotranspiration for the period (\( PET_0 \)), is the PED and is incremented on a daily basis.

\[ PED = PED_{d-1} + (PET_0 - RET) \]

In effect, PED is approximately equivalent to the amount of water that would need to be added by rainfall or irrigation to keep pasture growing at its daily potential rate.
Appendix 31  Irrigation scheduling scenario results at Larundel Dairy Farm (LDF), Three Springs Dairies (TSD) and Pendo Farms (PF).

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Note: Irrigation was applied when the plant available water fell below the ‘trigger’ value, which is relative to field capacity. mm refers to the depth of irrigation water applied, RI is the minimum irrigation return interval in days, I is the total irrigation applied, D is the total drainage, RO the total runoff, and T and E the total canopy transpiration and soil water evaporation, respectively, the units for each of which are mm. Y is the total herbage yield presented as t DM/ha.