Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.
ASPECTS OF THE WATER BALANCE OF AN OATS CROP GROWN ON A LAYERED SOIL

A thesis presented in partial fulfilment of the requirements for the Degree of Doctor of Philosophy in Soil Science at Massey University

BRENT EUAN CLOTHIER
1977
The increasing pressure on our water resources, for irrigation in particular, has resulted in a growing awareness of the importance of water balance studies. In this thesis three aspects of the field water balance are investigated: evapotranspiration (ET) from well-watered crops, the upper limit of soil water storage in the field, and drainage.

Daily ET values, measured by the Bowen ratio-energy balance method, are presented for an oats crop grown in winter and also for a number of summer crops, all of which were well-watered. ET measurements were also made over longer periods using a drainage lysimeter. It was found that the Penman, and Priestley and Taylor ET estimation procedures predicted ET with an accuracy of 15-20% and 8% for daily and weekly periods, respectively. The Priestley and Taylor method is simpler to use but requires an empirical constant to relate the 'equilibrium ET' to ET. This constant was found to be 1.21 for winter, spring and summer over a range of crops in the Manawatu. Net radiation data on a daylight basis were used to evaluate this constant, as seasonal variations in the constant were introduced when 24-hour data were used. Also it is easier to empirically estimate daylight than 24-hour net radiation. Long term ET estimates using the Priestley and Taylor method with net radiation calculated from incoming solar radiation, were in reasonable agreement with the drainage lysimeter measurements of ET for the oats crop.

A theoretical development is presented that describes water retention in soils underlain by a coarse-textured stratum. This development accounts for the physical character of the overlying soil, the depth to the coarse layer, and the coarseness of the underlay. Field data are presented for the Manawatu fine sandy loam, a soil with a coarse-textured layer at 90 cm. For this soil the layering resulted in an additional 55 mm of water
storage at the cessation of drainage, an increase of 31% over a similar hypothetical soil with the coarse stratum absent.

Drainage from a permeable soil underlain by a coarse-textured layer is investigated. Simplified theory is used to develop a model relating the drainage flux at the base of the soil to the water stored in the overlying soil. Despite significant hysteresis in both the water retentivity curve of the overlying soil and the hydraulic conductivity-pressure potential relationship of the coarse layer, hysteresis had little effect on the storage-flux relation. The model simulated both the field drainage in the Manawatu fine sandy loam measured by a lysimeter, and field profile water storage found by neutron probe moisture measurements. The model indicates that only simple field measurements are needed to find the storage-flux relationship.

The components of the water balance of an autumn-sown oats crop grown in the Manawatu are resolved. Drainage loss was found to constitute 60% of the rainfall, with the remaining amount being lost as ET.
ACKNOWLEDGEMENTS

I express my sincere thanks to my supervisors, Drs. Dave Scotter, Jim Kerr and Max Turner for their direction, encouragement and friendship during all the stages of my work. I would also like to thank Prof. Keith Syers and Dr Ken Mitchell for making it all possible. This work was carried out whilst I held a U.G.C. Postgraduate Scholarship and the 1974 B.P. (N.Z.) Postgraduate Scholarship, for which I am grateful. To the D.S.I.R. I am grateful for the help that enabled me to do this work.

Thanks also to John Talbot, Peter Menalda, Peter Rollinson and Jim Gordon for assistance both in the field and laboratory.

To Penny Clothier, thanks for the continual encouragement and warm understanding.

For much typing I wish to thank Erin Temperton.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Acknowledgements</td>
<td>iv</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>v</td>
</tr>
<tr>
<td>List of Figures</td>
<td>viii</td>
</tr>
<tr>
<td>List of Tables</td>
<td>xv</td>
</tr>
<tr>
<td>List of Symbols</td>
<td>xvi</td>
</tr>
</tbody>
</table>

## CHAPTER 1

**WATER BALANCE STUDIES** ........................................... 1
1.1 INTRODUCTION .................................................................. 2
1.2 THE FIELD WATER BALANCE EQUATION ................................ 2
  1.2.1 EVAPOTRANSPIRATION (ET) ...................................... 3
  1.2.2 MAXIMUM PROFILE WATER STORAGE \( W_{\text{max}} \) .......... 8
  1.2.3 PROFILE DRAINAGE (J) ........................................ 12
  1.2.4 SUMMARY ................................................................ 15
1.3 MATERIALS AND METHODS ............................................. 17

## CHAPTER 2

**MEASURED AND PREDICTED EVAPOTRANSPIRATION FROM WELL-WATERED CROPS** 19
2.1 INTRODUCTION .................................................................. 20
2.2 EXPERIMENTAL METHODS AND MATERIALS ................................ 22
2.3 RESULTS ......................................................................... 26
2.4 CONCLUSIONS AND SUMMARY .......................................... 39

## CHAPTER 3

**WATER RETENTION IN SOIL UNDERLAIN BY A COARSE-TEXTURED LAYER** 40
3.1 INTRODUCTION .................................................................. 41
3.2 THEORY ........................................................................... 43
3.3 EXPERIMENTAL METHODS AND MATERIALS ................................ 53
3.4 RESULTS ......................................................................... 57
3.5 SUMMARY AND CONCLUSIONS .......................................... 61
## CHAPTER 4

DRAINAGE FLUX IN PERMEABLE SOIL UNDERLAIN BY A COARSE-TEXTURED LAYER

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1 INTRODUCTION</td>
<td>63</td>
</tr>
<tr>
<td>4.2 THEORY</td>
<td>64</td>
</tr>
<tr>
<td>4.3 MATERIALS AND METHODS</td>
<td>65</td>
</tr>
<tr>
<td>4.4 RESULTS AND DISCUSSION</td>
<td>66</td>
</tr>
<tr>
<td>4.5 CONCLUSION</td>
<td>71</td>
</tr>
</tbody>
</table>

## CHAPTER 5

CONCLUSIONS AND SUMMARY

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1 THE OVERALL WATER BALANCE</td>
<td>87</td>
</tr>
<tr>
<td>5.2 SUMMARY OF RESULTS</td>
<td>88</td>
</tr>
</tbody>
</table>

## APPENDIX I

ERROR ANALYSIS OF THE BOWEN RATIO-ENERGY BALANCE METHOD OF ET ESTIMATION

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1.1 INTRODUCTION</td>
<td>94</td>
</tr>
<tr>
<td>A1.2 THEORY</td>
<td>95</td>
</tr>
<tr>
<td>A1.3 RESULTS</td>
<td>96</td>
</tr>
<tr>
<td>A1.3.1 ERROR CONTRIBUTION DUE TO THE PSYCHROMETER CONSTANT</td>
<td>97</td>
</tr>
<tr>
<td>A1.3.2 TEMPERATURE MEASUREMENT ERROR</td>
<td>100</td>
</tr>
<tr>
<td>A1.3.3 NET RADIATION MEASUREMENT ERROR</td>
<td>100</td>
</tr>
<tr>
<td>A1.4 DETERMINATION OF THE ERROR IN ET</td>
<td>102</td>
</tr>
</tbody>
</table>

## APPENDIX II

NEUTRON PROBE CALIBRATION

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2.1 INTRODUCTION</td>
<td>103</td>
</tr>
<tr>
<td>A2.2 THEORY</td>
<td>104</td>
</tr>
<tr>
<td>A2.3 EXPERIMENTAL</td>
<td>106</td>
</tr>
</tbody>
</table>
APPENDIX III

SCIL PROFILE DESCRIPTION .......................... 109
A3.1 SPATIAL VARIATION ............................. 110
A3.2 PROFILE DESCRIPTION ........................... 110

APPENDIX IV

CROP DESCRIPTION ..................................... 114
A4.1 INTRODUCTION .................................... 115
A4.2 CROP AGRONOMY .................................. 115

BIBLIOGRAPHY ........................................... 118
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig.1.1</td>
<td>Penman and Thornthwaite estimates of weekly ET for Palmerston North over the summer of 1974/75 compared to estimates using Priestley and Taylor's method ((ET\ (P\ &amp;\ T))) (After Clothier et al. 1975)</td>
<td>7</td>
</tr>
<tr>
<td>Fig.1.2</td>
<td>Water content at 30 cm depth in uniform soil, and the same soil underlain by sand at 61 cm and 122 cm depths and by gravel at 122 cm, as affected by the time after irrigation. Surface evaporation prevented (After Miller, 1969)</td>
<td>14</td>
</tr>
<tr>
<td>Fig.1.3</td>
<td>Comparison of predicted drainage flux (Eq. 1.6) with that measured for the Yolo loam, Miller silty clay and Cobb loamy sand (After Davidson et al. 1969).</td>
<td>16</td>
</tr>
<tr>
<td>Fig.2.1</td>
<td>Comparison of measured evaportranspiration ((ET)) against computed Penman estimates ((ET_P)), for oats. The correlation coefficient ((R)) and (S_{yx}) apply to the linear regression equation.</td>
<td>27</td>
</tr>
<tr>
<td>Fig.2.2</td>
<td>Comparison of measured ET against the 24 hour value of the equilibrium evaporation rate ((ET_{eq})) for oats, (S_{yx}) calculated for the regression line constrained through the origin.</td>
<td>28</td>
</tr>
<tr>
<td>Fig.2.3</td>
<td>Comparison of measured ET against the daylight (ET_{eq}), for oats.</td>
<td>30</td>
</tr>
</tbody>
</table>
Fig. 2.4 Regression of incoming solar radiation ($K_\downarrow$) against the net radiation ($R_n$) measured over oats. Both the 24 hour and daylight regressions are shown.

Fig. 2.5 Ratio of daylight $ET/ET_{eq}$ (i.e. $\alpha$) for oats from winter to early summer. Days when free water was noted on the crop are indicated (•). The mean monthly temperature is shown. The limits on $\alpha$ of 1 and $(s+\delta)/s$ suggested by Eq. 2.3 are also shown (--). 

Fig. 2.6 Predicted $ET$ (1.22 $ET_{eq}$) for selected periods against the $ET$ measured from a water balance applied to the lysimeter growing oats. The error band is ± 0.05 (rainfall) over the period.

Fig. 2.7 Comparison of measured $ET$ over oats (□) and lucerne, paspalum or pasture (○) against the daylight $ET_{eq}$.

Fig. 3.1 Variation in the water retentivity curve due to changing the value of the pore size distribution index $\lambda$.

Fig. 3.2 The pressure potential profile in a layered soil and in a uniform soil at the cessation of drainage.

Fig. 3.3 The increase in storage $\Delta W$, as a function of the pore size distribution index $\lambda$, for varying $\psi_i$, the cut-off potential in the underlay. Inset. The increase in storage as a function of $\psi_i$ for $\lambda = \lambda_{max}$. 
Fig. 3.4 The increase in storage $\Delta W$, as a function of the pore size distribution index $\lambda$, for varying $z_i$ the soil depth. Inset. The increase in storage as a function of $z_i$ for $\lambda = \lambda_{\text{max}}$  

Fig. 3.5 The increase in storage $\Delta W$, in a soil with secondary layering at depth $z_L$. The subscript '1' refers to the soil $z_L < z < z_i$ and '2' to the soil $0 < z < z_L$. Inset. The increase in storage as a function of $\lambda_2$ for $\lambda_1 = \lambda_{\text{max}}$  

Fig. 3.6 Drying water retentivity curves for the three profile elements of a Manawatu fine sandy loam  

Fig. 3.7 Hydraulic conductivity curves for two of the profile elements of a Manawatu fine sandy loam. Drainage is considered negligible when $K < 10^{-1}$ cm/day  

Fig. 3.8 Field tensiometer pressure potential data showing the decline in potential for a Manawatu fine sandy loam following a heavy winter rainfall of 29 mm. Over the subsequent 35 day period evapotranspiration losses of 70.5 mm were offset by 19 small rainfalls totalling 66.2 mm  

Fig. 3.9a Predicted profiles of water content in a Manawatu fine sandy loam, with and without the gravelly coarse sand layer
Fig. 3.9b  Field neutron probe data for a Manawatu sandy loam compared with the predicted profile of water content .......................... 60

Fig. 4.1  The water retentivity curves for the three profile elements of a Manawatu fine sandy loam. Measured hysteresis loops (→) and computed scanning curves (•→•) are shown for the gravelly coarse sand and fine sand. The scanning loops for various soil profile depths are shown for the fine sand. Field data for the fine sand (■) and fine sandy loam (●) are also presented ........................................ 68

Fig. 4.2  Hydraulic conductivity curves for all three profile elements of a Manawatu fine sandy loam ................................. 69

Fig. 4.3  Predicted wettest and driest profiles (ignoring evapotranspiration) of water content in a Manawatu fine sandy loam. The two wettest and driest water content profiles recorded between May and September 1975 are also shown ..................... 73

Fig. 4.4  Measured tensiometer pressure potential in the gravelly coarse sand at 100 cm depth during the winter of 1975, and predicted tensiometer pressure potential in comparison with field measurements at depths of 40 cm and 60 cm in the soil profile................. 75
Fig. 4.5 Predicted wetting and drying drainage flux – profile water storage relationships for a Manawatu fine sandy loam

Fig. 4.6 Predicted decline in profile water storage with time in comparison with that measured by the neutron probe at two sites following two heavy winter rainfalls

Fig. 4.7 Predicted decline in drainage flux with time in comparison to the drainage flux computed from the neutron probe data in Fig. 4.6, and the mean of that measured by the lysimeter over four drainage events

Fig. 4.8 Neutron probe profile water content data at two sites, in comparison with that predicted for 1974 and 1975. Also, the drainage flux predicted, in comparison with that measured by the lysimeter in 1974 and 1975

Fig. 4.9 Predicted drainage in relation to that measured by the lysimeter, for both 1974 and 1975

Fig. 4.10 The decline in profile water storage for a uniform soil of fine sand, predicted using the model of Black et al. (1969), in comparison to the decline predicted for a fine sand underlain by a layer of gravelly coarse sand using Eq. 4.6

Fig. A1.1 Ratio of the psychrometer to the psychrometric constant as a function of the aspiration flow rate for four different experimental runs
Fig. A1.2 Comparison of daily net radiation measured by two different net radiometers. The daily total of one found by integration of 1 minute sampling on a data logger and the other by analogue integration.

Fig. A2.1 Soil moisture content (cm³/cm³) in comparison with the count ratio. Also shown is the calibration curve supplied by Troxler.

Fig. A3.1 The profile of Manawatu fine sandy loam.

Fig. A3.2 The interface between the fine sand and gravelly coarse sand of Manawatu fine sandy loam. The range in height of the interface in this photo is 10 cm.

Fig. A4.1 Seasonal changes in yield components and dry matter % (Dm) of total forage for the 1974 oats crop (After Kerr and Menalda, 1976).

Fig. A4.2 Seasonal changes in the height and leaf area index (LAI) of the 1974 oats crop.
LIST OF TABLES

Table 1.1  Estimates of the available water storage based on $W_{\text{max}}$ at a pressure potential of -340 cm, in relation to that observed in the field, for 4 soils underlain by a coarse layer. (Miller, 1969) ....................... 11

Table 2.1  Comparison of monthly values of 1.22 ET$_{\text{eq}}$ and Penman estimates of evapotranspiration (ET$_{\text{p}}$) for Palmerston North ................................. 36

Table 3.1  Physical characteristics of Manawatu fine sandy loam ............................. 55

Table 5.1  Estimates of the components of the water balance of oats grown in the Manawatu during 1974 and 1975. The figures in brackets are the values of the components in terms of % rainfall. Also shown is the mean rainfall (1941-1970). All values in mm ................................. 89

Table A3.1  Profile description of the Manawatu fine sandy loam ............................. 111
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>empirical constant in Eq. 1.3</td>
<td>dimensionless</td>
</tr>
<tr>
<td>b</td>
<td>exponent in Eq. 1.3</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>convective term in the combination</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>C.R.</td>
<td>counts per second in soil/counts per</td>
<td>dimensionless</td>
</tr>
<tr>
<td></td>
<td>second in neutron probe radiation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>shield</td>
<td></td>
</tr>
<tr>
<td>$C_p$</td>
<td>specific heat capacity of air</td>
<td>J g$^{-1}$ C$^{-1}$</td>
</tr>
<tr>
<td>$d$</td>
<td>soil depth</td>
<td>cm</td>
</tr>
<tr>
<td>$D$</td>
<td>soil water diffusivity</td>
<td>cm$^2$ day$^{-1}$</td>
</tr>
<tr>
<td>$D_m$</td>
<td>plant dry matter</td>
<td></td>
</tr>
<tr>
<td>$\Delta p$</td>
<td>change in surface water detention</td>
<td>mm</td>
</tr>
<tr>
<td>e</td>
<td>vapour pressure</td>
<td>mb</td>
</tr>
<tr>
<td>$\Delta e$</td>
<td>difference in vapour pressure between</td>
<td>mm</td>
</tr>
<tr>
<td></td>
<td>two levels above crop</td>
<td></td>
</tr>
<tr>
<td>$e_s$</td>
<td>saturated vapour pressure</td>
<td>mb</td>
</tr>
<tr>
<td>ET</td>
<td>evapotranspiration</td>
<td>mm day$^{-1}$ or W m$^{-2}$</td>
</tr>
<tr>
<td>$ET_p$</td>
<td>Penman's evapotranspiration estimate</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>$ET_{eq}$</td>
<td>equilibrium evapotranspiration rate</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>$ET_{eq}^d$</td>
<td>daylight equilibrium evapotranspiration rate</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>$ET_{eq}^n$</td>
<td>nocturnal equilibrium evapotranspiration rate</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>$f(u)$</td>
<td>wind function in Penman's equation</td>
<td>mb$^{-1}$</td>
</tr>
<tr>
<td>$f(w)$</td>
<td>drainage flux-profile storage relationship</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>$G$</td>
<td>soil heat flux</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>$H$</td>
<td>sensible heat flux</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>$J$</td>
<td>drainage flux</td>
<td>mm day$^{-1}$</td>
</tr>
<tr>
<td>$J_i$</td>
<td>drainage flux in coarse underlay</td>
<td>mm day$^{-1}$</td>
</tr>
</tbody>
</table>
K  hydraulic conductivity
K_i  hydraulic conductivity of the coarse underlay
K_f  hydraulic conductivity of the overlying soil
K_s  saturated hydraulic conductivity
K↓  incoming solar radiation

L  latent heat of vapourization
LAI  leaf area index
L_1, L_2  characteristic length of soil particles
m  slope of the K-log_e(θ) curve
P  atmospheric pressure
Ph  energy used in CO_2 fixation by photosynthesis

r_s  crop resistance to water vapour
R_n  net radiation

RO  run off
RF  rainfall
R  simple correlation coefficient
S.D.  standard deviation
△S  crop heat storage change

s  slope of the saturated vapour pressure-temperature curve
S_yx  standard error of the regression estimate
T  mean daily temperature
T_{max}  maximum daily temperature
T_{min}  minimum daily temperature
T_d, T_W  dry bulb, wet bulb temperature
△T_d, △T_W  dry bulb, wet bulb temperature difference between two levels above crop

UNITS

- cm day^{-1}
- cm day^{-1}
- cm day^{-1}
- cm day^{-1}
- mm day^{-1} or Wm^{-2}
- Wm^{-3}
- dimensionless
- mm
- mb
- mm day^{-1} or Wm^{-2}
- sec cm^{-1}
- mm day^{-1} or Wm^{-2}
- mm
- dimensionless
- mm day^{-1} or Wm^{-2}
- mb C^{-1}
- c
- c
- c
- c
- c
t  time
u  windspeed

VPD  saturation vapour pressure deficit
W  profile soil water storage
W_t  profile soil water storage at time t
W_u  uniform soil profile water storage
W_L  layered soil profile water storage
ΔW  W_L - W_u
W_max  maximum profile soil water storage
W_min  minimum profile soil water storage
z  soil depth measured from soil surface
z_i  soil depth to coarse layer interface
z_L  soil depth to secondary layering
z_o  aerodynamic surface roughness
z  depth defined by Eq. 3.8

α  empirical constant, ET/ET_{eq}
β  Bowen ratio
γ  psychrometric constant
γ*  psychrometer constant
δ  error operator
η  slope of the log K- logΘ curve
Θ  volumetric soil water content
Θ_t  volumetric soil water content at time t
Θ_s  saturated volumetric water content
Δγ  difference between γ* and γ (Eq. A1.12)
λ  pore size distribution index
λ_{max}  pore size distribution index when d (ΔW)/dλ = 0

UNITS

<table>
<thead>
<tr>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>day</td>
<td></td>
</tr>
<tr>
<td>m sec^{-1} or km day^{-1}</td>
<td></td>
</tr>
<tr>
<td>mb</td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
</tr>
<tr>
<td>cm</td>
<td></td>
</tr>
</tbody>
</table>

dimensionless

mb C^{-1}

mb C^{-1}

cm^3 cm^{-3}

cm^3 cm^{-3}

mb C^{-1}

dimensionless

dimensionless
\( \xi \)  
ratio of the molecular weight of water to air  
dimensionless

\( \rho_b \)  
soil bulk density  
g cm\(^{-3}\)

\( \tau \)  
time  
day

\( \psi \)  
tensiometer pressure potential  
cm

\( \psi_e \)  
air entry pressure potential  
cm

\( \psi_c \)  
pressure potential when \( J = 1 \) mm day\(^{-1}\)  
cm

\( \psi_i \)  
pressure potential when \( J_i = 1 \) mm day\(^{-1}\)  
cm